Science Advisory Board (SAB) Economy-Wide Modeling Panel Draft Workgroup Responses to Charge Questions to Assist Meeting Deliberations. This draft is a work in progress, does not reflect consensus advice or recommendations, has not been reviewed or approved by the chartered SAB and does not represent EPA policy. -- Do Not Cite or Quote –April 24, 2017

Contents

Acronyms and Abbreviations

CGE	Computational General Equilibrium
DSGE	Dynamic Stochastic General Equilibrium
ECA	Engineering Cost Assessment
EWM	Economy-Wide Model or Modeling
GE	General Equilibrium
IO	Input-Output
PE	Partial Equilibrium
SAM	Social Accounting Matrix
VSL	Value of a Statistical Life
WTP	Willingness to Pay

1. EXECUTIVE SUMMARY

The National Center for Environmental Economics in the EPA Office of Policy requested advice from the SAB on the use of economy-wide modeling (EWM) for assessing the benefits and costs of air regulations. The agency's current approach uses detailed engineering-based compliance cost assessments and partial equilibrium (PE) market models for estimating social costs, and PE models for estimating benefits as well. EPA asked the SAB to: (1) evaluate the technical merits, methodological challenges, and potential value of using economy-wide models as a supplement to these tools; and (2) to suggest paths forward that would improve the usefulness of economy-wide models for regulatory analysis. In response to the EPA's request, the SAB convened an advisory panel on Economy-Wide Modeling of the Benefits and Costs of Environmental Regulation. The panel held a series of public meetings and teleconferences to deliberate on the charge questions. This report provides the findings and recommendations of the SAB in response to the charge questions (Appendix A).

The EWM approach that has been used most extensively for environmental policy analysis is general equilibrium (GE) modeling. Pure GE models have two distinctive characteristics: (1) equilibrium prices that cause all markets to clear at all times; and (2) all budget constraints are strictly enforced. Some recent models relax one or the other of these restrictions for some markets or agents. However, these characteristics are at the heart of the value added of EWM above and beyond PE analysis, so for clarity we will generally refer to economy-wide models as GE models. When discussing computational rather than analytical models, we'll use the term CGE, for computational general equilibrium.

An overarching issue in applying GE modeling to analysis of air regulations is the degree of detail, or granularity, in the model to be used. The ideal model would include fine-grained treatment of: (1) industries and products; (2) production processes; (3) geographic regions; (4) skills and occupations of workers; and (5) other demographic characteristics. No such model currently exists, nor is adequate data available to build one. Moreover, a model with that level of detail would be unwieldly to use and opaque to outside observers. As a result, a consistent theme in our detailed guidance below is that it will often be necessary and appropriate for EPA to link GE models to more detailed PE models. Linked models will usually involve some degree of inconsistency between their components but that will often be acceptable given the increased degree of detail that a linked analysis could provide. Linking is discussed further in Section 3.6.

Detailed findings and recommendations follow in the order of EPA's charge questions.

1.1 Measurement of Social Costs

1.1.1 Broad advantages and disadvantages of an economy-wide approach

GE analysis is not always required: a PE model may be sufficient for analysis of a policy expected to have limited impacts outside the industry where it is imposed. With that said, there are two broad arguments for augmenting a PE analysis with a GE analysis. First, a GE model can capture important interactions between markets, if *both* of the following are present: (1) significant cross-price effects, where a costly policy in one market drives consumers to buy more of a substitute or less of a complement good from another industry; and (2) significant distortions are present in those other markets. Second, a GE model can provide a consistent and comprehensive accounting framework to combine effects of a policy change on the cost side and the benefit side in a way that satisfies all budget and resource constraints simultaneously.

A frequent obstacle to GE analysis is the relatively aggregated structure of available models. However, as discussed in Section 3.6, it may be possible to overcome that by linking the GE model to one or more detailed PE models.

1.1.2 Factors affecting the merits of an economy-wide approach

Relative magnitude of the abatement costs of the rule

There is no bright line defining the abatement costs at which GE analysis is clearly warranted. However, the case is strongest when the costs of abatement are large relative to the value of the economy's aggregate factor income and the target sector has strong linkages with the rest of the economy. GE analysis will be useful for smaller shocks as well although the implicit precision of the model will limit its ability to provide useful results for very small shocks. Moreover, the model's degree of aggregation is important. For small shocks affecting a narrow component of a broad, highly aggregated sector, CGE models may add little insight or, worse, provide false precision. In contrast, a larger shock that would affect most of the firms in a given sector would be a much better candidate for CGE analysis.

Time horizon for implementation of the rule

Economy-wide models include modules that track important variables that evolve endogenously over time including capital stocks, savings, levels of public and private debt, and in some cases, the level of technology. It is a thus a priority for policies that could have significant impacts on those variables, or on important drivers such as the prices of capital goods, or international capital flows. For policies that affect those variables but which are phased in over time, the use of a model with foresight may be particularly important. A clear cut case where these features are particularly important, and where EPA has had a long tradition of using such models, has been the analysis of climate policy.

Number and types of sectors affected

There is no hard and fast rule for the number or type of sectors affected that justifies a CGE approach; rather, the considerations should be those noted above: whether there are strong cross-price effects between markets, and whether pre-existing distortions are present in those markets. With weak cross-price effects and small distortions, a multi-market partial equilibrium approach that may be adequate. With that said, there is a prima facie case for economy-wide modeling for policies with wide impacts.

Level of detailed needed to represent the costs of the rule

Finding an appropriate way to represent a narrowly targeted regulation in a highly aggregated GE model can be very difficult and modeling the transition costs of switching between technologies within a sector presents very formidable modeling and data requirements. In some cases, it may be possible to build an GE model that disaggregates the production processes subject to regulation. That is most likely for rules with large compliance costs that fall on narrow and well-documented segments of the economy, such as the electric sector. In other cases it may be necessary to link the GE model with a detailed engineering or PE sectoral model.

Appropriate degree of foresight

In general, a strong theoretical case can be made for solving economic problems in a forward-looking manner. However, such models can be considerably more complex to build and solve than models using recursive dynamics (that is, without foresight), and are more highly aggregated as a result. When foresight and a high degree of detail are both required, a linking approach (see Section 3.6) may be appropriate: an intertemporal CGE model can be linked to a detailed partial equilibrium model of the target sector.

International, fiscal and primary factor closure

Economy-wide models should treat the United States as a large open economy and the representation of international trade should include some form of product differentiation between imported and domestic goods. However, the specific approach used to model imports and exports may depend on the regulation being considered. Global multi-region models include a full representation of each economy as they interact in international markets. This class of models is most appropriate when a policy has important general-equilibrium impacts across regions. For other research questions it may be more appropriate to use a more detailed stand-alone open-economy model of the U.S. abstracting from a full representation of the foreign economies. In either case, there is significant debate in the literature regarding the parameterization of trade responses, and it is important to recognize the challenges and note resulting model sensitivities to imprecisely measured parameters.

The treatment of international capital flows is also important. Policies that raise or lower rates of return on investments in the U.S. will lead to capital inflows or outflows through portfolio arbitrage by international investors. These effects can be particularly important for policies announced in advance: capital can flow into or out of the U.S. in anticipation. An important note of caution is warranted for stand-alone models: it is generally inappropriate to assume that the U.S. faces a fixed interest rate in international capital markets.

Endogenous supplies of primary factors are another key aspect of model closure. An important example is household labor-leisure choice, which endogenously determines the adjustment of labor participation and hours in response to changes in relative prices. A second example, as noted above, is capital accumulation. Capturing these effects is a key strength of economy-wide modeling.

Finally, general equilibrium interactions between policy changes and pre-existing distortionary taxes can substantially change the social costs of a policy. This points to the importance of accounting for such interactions when measuring economy-wide costs (as noted in Section 3.1), especially when the policy affects factors of production. This highlights a third aspect of closure, namely assumptions regarding the government's budgetary balance and fiscal components of regulations that are price-based and generate substantial tax revenue. These assumptions have been shown to be quite important for a wide range of policy cases, from economy-wide taxation of GHG emissions to more narrowly targeted regulations that primarily involve pollution control mandates.

Availability and cost of economy-wide models

A given analysis will need to take one of the following approaches: (1) develop a new CGE model that will be highly suited to the analysis; (2) use an existing CGE model that is less well suited; (3) use a small analytic model to capture economy-wide tradeoffs with less detail than a full CGE model would provide; and (4) to omit economy-wide analysis and focus on partial equilibrium analysis alone.

Because the cost of developing a robust CGE model is very high, a new model should only be developed when: (1) general equilibrium effects are expected to be large, (2) adequate data are available to parameterize the model credibly at the level of detail needed for the analysis; and (3) the model will be flexible enough to be used for multiple analyses. In other circumstances, an existing model (perhaps linked to a detailed PE sectoral model) could be used. When no appropriate model is available and the regulation in question doesn't warrant the development of a new model, an analytical approach could be used. Finally, GE analysis could be omitted if it is unlikely that significant costs will be omitted from a PE analysis.

Ability to incorporate uncertainty

Uncertainty is inherent in all analysis and not specific to economy-wide modeling. However, because the number of parameters in a typical economy-wide model is large, characterizing uncertainty in a transparent and systematic way is particularly important. In some circumstances, confidence intervals can be derived from the covariance matrices of the model's parameter estimates and reported along with model results. When that is not feasible, it will usually be necessary to use sensitivity analysis. Appropriate practices for characterizing uncertainty are discussed in detail in Section 6.4.

1.1.3 Other factors to be considered

Compliance with information quality standards

Economy-wide models, and the data on which they are based, should comply with government-wide information quality standards. As a result, EPA should follow previous guidance of the National Research Council and move toward using non-proprietary models, where the definition of non-proprietary includes source code, third-party software, and input data. Proprietary data and models generally cannot satisfy applicable information quality standards for procedural transparency because they are not capable of being reproduced by qualified third parties. In addition, the outputs of economy-wide modeling are also subject to information quality standards. Procedurally, results must be capable of being reproduced by qualified third parties. This means access must be provided on request, including comprehensive model documentation and computer code.

Availability of appropriate data

The availability of data on production is a very significant factor to consider in determining when it is appropriate to use GE modeling, and it imposes significant tradeoffs. Given the underlying data sources available on production, it is not possible to have a model that is simultaneously: (1) highly disaggregated; (2) based on flexible functional forms; and (3) parameterized with a large number of degrees of freedom. Hence, data limitations are the fundamental obstacle to high granularity in GE models.

Representation of labor transition costs

Transition costs in the labor market, which will be discussed in detail in Section 5 on impacts, can potentially contribute to overall social costs as well. To the extent that the earnings loss represents a net social cost (as opposed to a purely distributional effect), that cost would be omitted by any model that ignores labor transition costs. To capture these costs in a CGE model would require a dynamic model that generates large and persistent earnings losses following a layoff. Some CGE models are moving in that direction, and as noted in Section 6.5, a near term priority for EPA should be to encourage further development of CGE models with involuntary unemployment. Employment aspects of economy-wide modeling are discussed in more detail in Sections 5.4 and 5.5.

Other modeling choices

As discussed in Section 3.1, existing taxes, subsidies or other policy distortions play a critical role in GE analysis and should be included wherever possible in the model. In addition, imperfect competition may be important for some regulations. The corresponding literature in environmental policy is relatively new and EPA should encourage further development of it over the near to longer term. Finally, regulatory policies may have impacts on productivity growth and technological change; modeling these explicitly can be challenging but is a desirable feature.

1.1.4 Challenges in modeling regulations

Non-price regulations have often been modeled in the literature as adverse shocks to the productivity of the regulated industries. It is also possible that non-price regulations could be modeled as their price-equivalents using tax and subsidy combinations. Alternatively, if EPA has identified the specific technology it expects industry to use to comply with the regulation it may be useful to link a detailed PE model of the sector to the GE model. With all approaches, the more granular the spatial, sectoral, temporal and legal rules embodied in the regulation, the more challenging it will be to represent in a GE model. For example, implementation of an ambient air quality standard can vary widely across air basins, making it difficult to capture in an economy-wide model. Moreover, the degree of compliance or non-compliance will vary by region.

An important caveat is that the least-cost compliance strategies typically assumed in GE models do not account for a number of rigidities in the real-world selection of compliance methods. Where appropriate data are available, long term development of GE models should move toward accounting for any such constraint that would have a significant effect on output. In the near term, GE analysis should note that these constraints are not included.

1.1.5 Appropriate metrics for social costs

Equivalent or compensating variations are the appropriate and preferred metrics for measuring the social costs of regulation. They are grounded in economic theory, have the potential to incorporate all impacts of regulation on households, and provide a dollar-based measure of social costs that can easily be compared to dollar-based measures of benefits. Alternative measures, such as changes in household consumption or changes in gross domestic product, have significant flaws and should be avoided.

1.1.6 Linking economy-wide and sectoral models

Federal air regulations are inherently sector- and region-specific in their costs and benefits, so some type of linking of bottom-up and top-down models will often be necessary to deliver national scale assessments of such regulations. A number of approaches for linking models are well-established in the literature. However, linked models all involve some degree of inconsistency and approximation and should be evaluated critically to ensure that they are appropriate for the analysis at hand. For full consistency between a technology-rich bottom-up model and a CGE model, it is necessary to embed the bottom-up technologies directly into the CGE model. This approach is most likely to be worthwhile for sectors that: (1) have many linkages with the rest of the economy; and (2) are likely to be the subject of recurring regulatory analysis. A good example is the electric sector.

1.1.7 Economy-wide approaches other than CGE modeling

Dynamic stochastic general-equilibrium (DSGE) models are conceptually similar to CGE models in that they are computational general equilibrium economy-wide models built upon microeconomic foundations. Standard DSGE models are not likely to be useful for EPA's purposes because they typically have far too little sectoral disaggregation. Nonetheless, there is potential for using DSGE methods to develop models that could be very useful for looking at issues that are hard to address with current CGE models, such as interactions between environmental regulations and business cycles. Other modeling approaches that are often used for economy-wide modeling, but are not recommended in their current form for use by EPA to analyze social costs, include input-output analysis and macroeconometric models. In some circumstances it may be best to use a suite of tools including both PE and CGE models: as discussed in Section 3.6, a hybrid analytical approach may be superior to a CGE model alone.

1.2. Measurement of benefits

1.2.1 Conceptual and technical hurdles in economy-wide modeling

The technical and conceptual hurdles to representing benefits from air pollution policy arise from the discrepancy between the highly granular nature of impacts from air pollution exposure and the highly aggregate structure of GE models. For example, even GE models with some degree of regional detail will not be able to capture the localized impacts of air pollutants that are not well mixed. However, it is possible to use a linked approach to break out local impacts from GE results when the economic feedbacks from the benefits of air pollution control are weak.

Conversely, if GE benefits of air regulations are not expected to vary across space then the aggregated GE approach may be adequate. For example, if the benefits of air pollution regulations are primarily reductions in premature mortality risks, and labor is relatively mobile, then a national-level analysis would not be biased and a spatially disaggregated CGE model would not be required.

A particular challenge in a spatially-disaggregated CGE approach is modeling future decisions about the locations of plant closures and new facilities. These prospective choices would be very difficult to make with any degree of precision and this component adds to the difficulties associated with using spatially-disaggregated CGE models.

1.2.2 Equivalent variation and willingness to pay for risk reductions

Equivalent variation (EV) measures derived from CGE modeling typically capture the increase in income or wealth that would provide the same gain in utility as would result from the added longevity associated with the regulation’s reduction in mortality. In contrast, most of the mortality benefits typically included in EPA’s benefit-cost analyses are calculated from PE measures of individual willingness to pay (WTP) for risk reductions. WTP measures are ex ante values of different gambles and are hence tightly connected to risk aversion and often to expected utility. However, they capture marginal WTP for small changes in risk and are not usually embedded in a complete demand system; hence, they could overstate benefits by failing to acknowledge the limits imposed by budget constraints and the effects of diminishing marginal utility. EV measures have almost the opposite characteristics: they are based on total, rather than marginal gains, and they include full enforcement of budget constraints. Reconciling the two measures would be valuable and would be best achieved by extending the utility functions used in GE models to include explicit treatment of risk aversion.

In the literature to date, WTP measures are often large relative to EV results from GE models. An important analytical challenge with current methodologies is thus to determine the general equilibrium impacts associated with those large WTP values. That is, when a change in mortality risk is brought about by regulation, and WTP estimates suggest that the value of the change is large, it is important to understand how the change impacts behavior and market variables. The integrated approach proposed above would capture those impacts directly. Moreover, it would allow non-separable treatment of reductions in risk or other kinds of improvement in environmental quality. That is, it could allow for the environment to be either a complement or substitute for some market-based activity. A GE model thus allows changes in environmental quality, including changes in mortality risk, to affect the responses of other parts of the economy to policy changes through non-separable relationships.

1.2.3 Public health and economic activity

The links between air regulations, public health and economic activity are complex and discussed in detail in responses to other charge questions. As noted in Sections 4.1 and 4.11, spatial heterogeneity may be important, both in concentrations of pollutants and in the demographic characteristics of populations exposed. As discussed in Section 4.2, air quality will have impacts on morbidity and mortality that affect the economy through changes in the effective labor supply. Section 4.5 provides further discussion of morbidity and mortality impacts and then goes further to discuss the impacts of air quality on: (1) the demand for health care, (2) the consequences of that care for health status, and (3) residential sorting among households with different willingness to pay for reduced health risks. Section 4.6 discusses the feasibility of linking health to changes in employment status that may result from regulatory changes. Section 4.7 provides discusses the link between health status and the demand for goods other than health care, as well as providing further discussion of the link between air quality and the demand for health care itself. Finally, Section 4.8 discusses the link between air quality and productivity.

1.2.4 Modeling impacts as changes in household time endowments

Modeling changes in mortality and morbidity risks as changes in the time endowment of households is technically feasible and widely supported in the literature. However, other channels for the impacts of pollutant exposure, such as labor force participation or changes in health care services and expenditures, should be considered as well. As noted above and in Section 4.2, a near term research priority would be to extend the utility functions used in GE analysis to go beyond changes in time endowments in order to capture risk aversion explicitly.

1.2.5 Other representations of mortality and morbidity

Benefit analyses for conventional air pollutants have usually used a damage function approach focused on morbidity and mortality. However, there is sufficient empirical support to begin augmenting that with hedonic estimates of the effect of air pollution on housing values. With that said, there are several difficulties applying this literature at the national level. Existing hedonic studies do not: (1) provide as much detail as damage function approaches on the impacts of specific pollutants; (2) offer sufficient coverage of different urban areas to be used on a national scale in lieu of the damage function approach; or (3) isolate health effects from other motivations for avoiding air pollution. Full integration of this literature into CGE modeling is a long term research task. However, hedonic property value estimates are useful in the near term as part of a plausibility analysis (discussed in detail in Section 6.1) of benefit assessments based on the conventional strategy.

In addition, to address the cost of morbidity fully, it is also necessary to incorporate the production and consumption of health care and how health care expenditures change the effects of pollution on morbidity and mortality. Choosing appropriate functional forms to represent substitution and complementarity relationships between environmental quality, health, health care, and other market and non-market goods would require a substantial research effort. A key challenge lies in distinguishing between the tradeoff measures for morbidity and those for mortality risk changes, since individual actions may have impacts on both.

1.2.6 Effects of employment changes on health status and crime

In principle, the effect of employment on health and crime can be incorporated into a CGE model. However, doing so in a plausible and credible manner would go well beyond the frontiers of current knowledge and would require major investments in model development. Given these difficulties and EPA's limited resources, we do not advocate incorporating these effects at this time, either in a CGE model or any other economy-wide model. It might be possible to pursue a simpler analytical GE approach focused specifically on this issue. EPA could pursue such research in an effort to understand whether this issue is potentially large enough to be relevant, in which case further efforts to include these effects in an economic impact assessment could be warranted.

1.2.7 Health status and changes in relative preferences

The complicated structure of the U.S. health care market means the link between ambient air quality and household medical expenditures is highly indirect. Households covered by employer-provided insurance, Medicare, Medicaid, or policies purchased through exchanges established under the Affordable Care Act will have out-of-pocket expenses that are only weakly correlated with actual medical costs. The bulk of any cost savings would thus accrue to private and public insurers and would not necessarily be passed back to individuals. Moreover, significant health benefits from reduced air pollution are expected to be concentrated among persons who are elderly, infirm or both. Such individuals are predominantly served by Medicare and Medicaid and would see little or no change in their medical care costs. Any cost reductions would be realized as reduced federal and state program expenditures, and thus a lower burden on taxpayers, rather than as lower costs to the individuals directly affected by air pollution.

This point bears on the approach used in the Second Section 812 Prospective study. Reduced medical expenditures attributed to lower air pollution were calculated by extrapolating from published cost-of-illness estimates and then interpreted as realized cost savings to individuals. The analysis thus implicitly assumed full pass-through of lower medical costs by insurers to employers and then to employees—a very strong assumption given the structure of the U.S. health care market. As a result, a preliminary step that should be taken before applying the 812 approach again is to conduct a rigorous and transparent evaluation of information quality and the validity of the model's assumptions about the extent to which any cost savings realized by third parties would pass through to consumers.

Incorporating preference changes due to reductions in air pollution should not be a near term priority for EPA. Formally, such individuals would have state-dependent utility functions. As a theoretical matter, state-dependence could be incorporated into a CGE model via modifications to the utility functions used to represent individual behavior. However, parameterizing those functions would be difficult and there is relatively little conclusive empirical evidence on state dependence. Moreover, although a large effect cannot be ruled out *a priori*, given the ambiguity of existing studies the effects are likely to be small relative to other impacts of regulation.

1.2.8 Incorporating productivity gains

Potential benefits from productivity gains of the workforce due to cleaner air may be important. However, the current literature is too narrow to provide the kind of national-level information about productivity impacts that would be required for a broad GE analysis. Instead, high-quality peer-reviewed industry-level studies, where they exist, could be used in detailed PE sectoral models linked to a GE model. Over time, an important role that EPA could play would be to encourage and support the collection, public disclosure, and analysis of data that improves the understanding of the productivity effects of regulation and of cleaner air on the workforce. EPA should consider broad integration of productivity gains of the workforce into CGE models to be a long term objective.

1.2.9 Impacts on non-market resources

An important long-term priority for EPA should be to encourage much more extensive incorporation of non-market resources into GE models. It should start by focusing on including environmental services with use values in utility functions with non-separable preferences, and then modeling the impact of emissions on the production of those services. Subsequent efforts should be directed toward extending the analysis to include environmental goods with non-use values. These are more challenging because by definition they do not have conventional behavioral impacts that can be used for parameterizing the utility function. However, recent work on valuation methods suggests that linking multiple private goods to environmental quality may allow such parameters to be inferred.

1.2.10 Interpreting results when some benefits cannot be modeled

Fully consistent treatment of benefits is challenging, especially when environmental services are not separable from market goods in the utility function, and when emissions impact the supply of such services. However, even if full consistency cannot be achieved a GE model can offer an important plausibility gauge and can serve as a basis for evaluating whether the GE effects of major rules are important enough to warrant modifying benefit-cost estimates developed using partial equilibrium methods.

An important caveat is that it will generally not be appropriate to sum CGE and PE benefits since they may not have been consistently calculated. Benefit-cost analyses should be very clear about the categories of benefits that are captured and those that are not. When some benefits cannot be modeled, it is important to frame the economy-wide results as capturing only a portion of total benefits while another portion remains outside the model.

1.2.11 Spatially distributed benefits

At a local or regional level, spatial sorting of heterogeneous households can have an important impact on the estimated benefits from improved air quality. However, it is reasonable to assume that changes in commuting behavior, wages and labor supply will be most strongly felt at the local level. At a national, or even state, scale, such spatial sorting is expected to have little impact on, for example, national labor supply. In the interest of prioritizing resources, spatial sorting should not be addressed in the near term in GE analysis.

Although modeling sorting within regions is a low priority, capturing differences between regions may be more important. It is now quite common to differentiate certain endowments spatially in CGE models. However, the existing literature has not examined the importance of differentiating between regions in national-level benefit calculations. To fill that gap EPA should sponsor a model comparison project that would compare the performance of disaggregated and national-level models in determining aggregate national measures of welfare. Such an analysis would indicate the relative importance of developing regionally-disaggregated GE models, which are difficult to build given available data and the high potential mobility of goods and factors between regions.

1.3. Evaluating Economic Outcomes

1.3.1 Appropriate use of CGE models

Broadly speaking, CGE models are appropriate and valuable for analysis of the economic impacts of air regulations. As noted throughout the report, however, it is not feasible or desirable to build a single CGE model with sufficient detail in all dimensions to be used for all purposes. Moreover, a balance must be struck between capturing detail and complexity, and providing transparency and tractability. As a result, CGE models will often need to be linked to more detailed PE models to capture all impacts of interest.

Short and long run implications of energy prices

CGE models have often been used to analyze the long run impacts of energy prices and are appropriate for that purpose. Short run analysis is less common but can be accomplished via a standard set of techniques in the literature for building short-run dynamics into CGE models. For example, adding capital vintaging, adjustment costs and limited substitution possibilities between factor inputs to CGE models are all accepted ways one can limit the response of the model to policy interventions in a way that is consistent with short-run outcomes.

When policies have spatially differentiated short run impacts, a model with regional disaggregation will be required. This is likely to be particularly important for policies affecting the electric sector due to regional differences in the sector's fuel mix. There has been a great deal of progress in building multiregional CGE models down to the census region, state or electric reliability region. Regional and fuel disaggregation is present in many models used to evaluate air regulations, and is the best practice to follow when regional differences in cost and price impacts are expected. However, this disaggregation can be complex to implement: it requires a structural representation of behavior, technology and prices at the chosen level of aggregation.

An additional factor that may complicate the estimation of energy price impacts is interactions between air regulations. The energy price impacts of a new or proposed policy will depend on the current attainment status of particular counties and metropolitan areas. A judiciously chosen degree of geographic resolution is necessary to capture these impacts. Disaggregation beyond the resolution of available economic data will provide no useful information about economic impacts. Since county-level data is insufficiently reliable and consistent to be used in economy-wide modeling, this suggests that judicious aggregation is required to minimize the first-order errors induced by mismatching air and political regions.

Sectoral impacts

As noted above, the sectoral aggregation of CGE models is central to whether they can adequately capture impacts of an air regulation. However, estimates of highly detailed within-sector impacts may require linkages to sector-specific PE models, even in CGE models with larger numbers of sectors. A linked CGE-PE model can potentially translate the GE effects of a policy into facility-level ramifications such as plant openings and closings and vice versa. Linking models is discussed in Section 3.6.

Impacts on income distribution

As noted above, a central issue concerning the suitability of a given CGE model to assess the effects of an air regulation is the model's degree of aggregation. For analysis of impacts on income distribution, a detailed decomposition of households into demographic groups and income categories is required; a highly aggregated model will omit very important distributional effects. Distributional effects also depend on how broadly income is defined. One level of analysis works strictly with income earned in the context of the market economy: wages, salary, and income from capital assets. An broader definition includes non-market components such as the value of leisure time, home production, consumption of natural capital, and adverse impacts from exposure to environmental pollutants. Using a broad notion of income is especially important in the analysis of air pollution regulations as such policy interventions will impact exposure and, hence, this augmented definition of income. CGE models would, in principle, be able to accommodate such an income construct so long as: (1) the components of augmented income are monetized, and (2) they are matched in aggregation according to the CGE structure.

Transition costs in capital or labor markets

Air regulations may have particularly concentrated impacts because such policies often target distinct sectors, industries, or facilities. One clear advantage of CGE relative to PE approaches is the ability to capture movements of workers or capital from a regulated sector to an unregulated or less regulated one. Such transitions often involve considerable and sometimes highly persistent costs. These costs may result from prolonged periods of involuntary unemployment, the need to retrain workers if human capital affected by an air regulation is particularly specialized, and the heterogeneity of transition costs within the income distribution. Transition costs associated with capital flows between sectors have long been included in CGE models that include adjustment costs in investment. Transitional search costs in labor markets have been added in recent models.

Equilibrium impacts on labor productivity, supply or demand
Broadly speaking, evaluating equilibrium labor market impacts is a core strength of CGE models and one of the most important benefits they provide relative to PE approaches. With that said, there is considerable room for improvement. Almost all CGE models use a highly aggregated approach to modeling labor markets and do not distinguish between different occupational or skill groups. CGE models generally do not have endogenous equilibrium wage differentials between different groups, nor do they have endogeneity in educational or occupational choice.

In terms of equilibrium impacts on aggregate productivity, CGE models provide useful but incomplete information. In the long term, productivity results from three forces: (1) increased educational attainment and human capital accumulation; (2) capital deepening; and (3) technical change. The first component, educational attainment, is generally imposed exogenously in CGE models. CGE results will thus fail to capture any productivity impacts of air regulations that would come about through changes in the amount of education workers choose. In contrast, CGE models that are relevant for air regulations all include endogenous capital accumulation and will thus capture capital deepening. The final component, technical change, varies across models: in some it is exogenous and in other models labor or total factor productivity is endogenous.

1.3.2 International competitiveness
The international considerations discussed in regard to social costs in Section 3.2.6 apply to the measurement of impacts as well. Overall, GE modeling is an appropriate and useful method for assessing effects on international trade, and also for determining the degree of leakage of emissions to other jurisdictions. However, when regulatory impacts are expected to be narrowly focused on a specific trade-exposed sector it may be advantageous to link the GE model to a more detailed sector-specific PE trade model.

GE models use well-established methods in the literature to treat foreign and domestic goods as differentiated products. Newer methods are beginning to refine those techniques to incorporate heterogeneity of firms within industries. Independent of trade impacts, the consideration of firm heterogeneity can improve modeling of impacts within industries by characterizing the pattern of regulatory burdens across firms with different emissions intensities. This may be particularly desirable because regulatory impact analyses may emphasize impacts on small firms.

Another area of modeling that is potentially useful for assessing the indirect effects of air regulations is GE analysis of regulatory impacts on global supply chains. Air regulations in an upstream sector might reduce the competitiveness of the given sector, but because of shifts in international sourcing, adverse economic effects on downstream sectors might be substantially mitigated. Multi-region CGE models can help identify the channels for such effects. Depending on the nature of regulations, identifying such channels might be quite important.

For regulation of criteria pollutants, an open-economy approach can be appropriate. For carbon policy, a multi-region approach might be necessary. In particular, when foreign regulation of carbon is coincidental to domestic regulation, the leakage and competitive effects depend on endogenous foreign-agent responses. While accounting for international competitiveness or leakage in a CGE model does not necessitate compromises in other modeling dimensions, it is important to use a transparent structure that informs the specific research question.

1.3.3 Criteria for evaluating CGE models used to assess impacts

The criteria for evaluating CGE models should be the same no matter where the model is developed. In addition to applicable information quality standards, the basic checks for any CGE model include: (1) availability, completeness and transparency of model documentation; (2) public access to the model, including its source code and all other material components; (3) a theoretically consistent structure based on microeconomic foundations that represents the behavior of producers and consumers; (4) theoretically and empirically sound justifications for the choice of functional forms and parameter values; (5) verification that common theoretical properties discussed in Section 6.1 hold; (6) exploration of underlying reasons for any markedly different results from other models; (7) peer-reviewed publications for the model or its closely-related antecedents; (8) substantial evidence of robustness with respect to alternative plausible assumptions, model specifications and data. Model performance should be tested via model comparison exercises and through simulations examining alternative assumptions, data, and sets of stylized facts. Reproducing history *per se* is not an appropriate measure to evaluate CGE models.

The advantages and drawbacks of CGE models for economic impact analysis are the same as advantages and drawbacks of these models for measuring social costs, which are discussed in Sections 3.1 and 3.2. A key challenge can be the relatively aggregated structure of GE models: the models available may have less detail than desired for analysis of some impacts. As noted above, it may be possible to address that by linking the GE model to a detailed, sector-specific PE model.

In terms of the labor market impacts, economy-wide models have the ability to capture interactions across markets, regions and household groups. CGE models consistently determine factor prices, including wages. However, most CGE models focus on the medium to long run and assume full employment and full mobility of workers between sectors. As a result, they do not fully capture the real-world short-run difficulties workers face from transitional unemployment and sectoral changes in labor demand. Additional aspects regarding the insights and shortcomings of CGE models for labor market impacts are discussed in Sections 5.1, 5.4 and 5.5.

As with estimates of costs and benefits, an appropriate degree of foresight is important for evaluating economic impacts. As discussed in Section 3.2.5, the perfect foresight assumption has an advantage relative to other settings in modeling savings behavior. However, it also increases the complexity of solution algorithms and tends to reduce the degree of sectoral detail in a given model. Thus, perfect foresight models may have less applicability to estimate the impacts of very small policy or regulatory changes or in the settings where detailed representation of sectors or households is needed.

1.3.4 Labor impacts under full employment closures

The vast majority of CGE models assume full employment, usually with labor supply changing endogenously in response to real wages. That can be appropriate for medium to long run analysis but it limits the short run labor impacts that a model can analyze. In particular, a full-employment model clearly cannot provide information about the extent and duration of any unemployment resulting from a regulation. Moreover, in discussing labor market impacts in full employment models it is essential to be clear that changes in overall employment are coming about because of voluntary labor supply decisions by workers in response to wages.

1.3.5 Modeling transition costs and factor market disequilibrium

Several methods are available for modeling labor market transition costs by relaxing the full employment assumption in most GE models. However, the most widely used and well-tested existing methods have serious drawbacks or limitations. In addition, at best they capture general unemployment in the economy as a whole, not sector-specific unemployment in the regulated industry. New approaches are highly promising, but are not yet be ready for practical use. In the near term, EPA should encourage further development of CGE models able to capture frictional unemployment. Development of models of structural unemployment should be considered a long term goal. Finally, efforts by EPA to develop models for air regulation that include endogenous business cycles is undesirable: given the current state of knowledge an easier and more transparent approach would be to apply sensitivity analysis to exogenous projections of business-cycle-driven unemployment.

Transition dynamics are more widely used in modeling capital. Methods include capital adjustment costs, putty-clay models, and vintage capital models. Adjustment costs could also be included in labor demand, although no such models appear yet in the environmental policy literature. Slow adjustment of prices could also be included but price stickiness (other than wages) is rare in environmental CGE models.

1.3.6 Other economy-wide approaches for modeling short run impacts

The most promising approach other than CGE models for capturing short run impacts is dynamic stochastic general equilibrium (DSGE) modeling. Current DSGE models usually have too little sectoral detail for routine use to evaluate air regulations. However, they have attractive characteristics for modeling uncertainty. With further development of the literature, DSGE models could become a valuable approach for assessing short run impacts. This is a long run task: much groundwork needs to be done.

In contrast, input-output and social accounting matrix models have severe limitations that render them far below the current state-of-the-art in comparison to CGE models. They would only be appropriate for very short-run impacts of a relatively small nature where substitution possibilities would be limited and price effects would be minimal. Other models that are not appropriate include: agent-based or microsimulation models, which are typically are not economy-wide; and systems dynamics models, which are not based on microeconomic foundations.

1.4. Additional considerations for economy-wide analysis of air regulations

1.4.1 Technical merits and challenges

The technical merits of using economy-wide models are the same as those identified in Section 3.1. The largest technical challenges revolve around the accurate representation of command-and-control regulations in economy-wide models and incorporating explicit structural representation of the externalities that air regulations are designed to address. Overall, GE analysis would be an appropriate supplement to PE analysis for many air regulations. However, GE analysis may not be required if the spillover effects of a regulation apply to only a limited number of markets.

As discussed throughout the report, CGE and PE models may be linked and GE model outputs can be used as inputs to PE models. This is particularly common in the case of using survey data to decompose GE household impacts to measure the differential incidence of a policy.

The models or tools chosen should line up with the problem being analyzed, both sectorally and spatially. There are potential pitfalls in geographic or sectoral aggregation that need to be addressed in each case. This is particularly true for pollutants where the spatial distribution varies, where there are complex atmospheric processes, or where sources are not distributed homogeneously.

The choice of models for a particular case can be made in a more informed way, and justified more convincingly, if models and data are publicly available in accordance with applicable information quality guidelines. It is also desirable to standardize some practices for testing the consistency of models.

Potential interactions between costs and benefits exist and much work remains to be done on representing non-separable benefits in CGE models. However, that does not invalidate the use of CGE models to estimate costs or make it impossible to design a consistent approach to both benefit and cost estimation. Even if non-market externalities are not estimated in a CGE model, the economy-wide approach can still yield useful information, particularly for cost-effectiveness analysis.

It may be more straightforward to incorporate separable benefits into a CGE framework than to design the structural representation of externalities necessary to incorporate non-separable benefits. However, there are benefits of even a rudimentary effort to model non-separable benefits in a CGE framework as opposed to PE: (1) including an income constraint on willingness to pay for nonmarket benefits; (2) closing the gap between WTP and EV measures of the value of mortality risk reductions; and (3) deriving the value of air quality improvements from a utility function will ensure declining marginal utility from improvements in air quality.

1.4.2 Imperfect measures of benefits

Encouraging development of fully integrated, non-separable treatments of environmental benefits in GE models should be a very high priority for EPA in the near to long term. Revealed preference methods have been at the center of benefit measurement in environmental economics for over 50 years and all of them must assume the tradeoffs that motive choices arise from non-separable relationships between market goods and services and nonmarket services. To date, there have been limited analyses of the implications of general equilibrium effects for benefit measures associated with environmental regulations. The literature that is available suggests that even small changes in these costs as a fraction of aggregate income can cause large discrepancies between PE and GE welfare measures.

In the interim, however, EPA should move in the direction of using GE models for estimates of social costs and economic impacts as noted above even though the GE analysis will not be fully consistent until benefit measures are improved.

Absolute measures or relative comparisons

It is not possible to evaluate, given the extent of the literature available, the merits of reporting findings in terms of the relative changes versus the presenting the welfare changes in levels. It is important to compare the welfare changes attributed to policies to the associated changes in other measures of economic activity that would be observable ex post. Long term use of GE would be strengthened by systematic assessment of a set of observable ancillary changes in economic activity that are predicted responses to regulation and can be estimated and documented. Relying on relative measures would not be consistent with this approach.

General v. partial equilibrium to assess net benefits

There are clear advantages to presenting both PE and GE measures: together they give a more complete picture of the impact of the regulation. A key challenge, however, is the need for a framework that describes the features of a policy that might give rise to differences between these two measures of benefits and costs. Such a framework has not been developed and evaluated in the published literature.

1.4.3 Presenting results

Whether discussing engineering, PE or GE models, the goal in describing the model and its results is to provide outside readers the information necessary to both understand and reproduce the results. To this end, the model's data, structure and code should be publicly available and proprietary models should not be used, if at all possible. EPA should make all PE and CGE models (including data and computer code) available to the public to encourage outside validation. In addition, best practices include providing the following in addition to simulation results: (1) tables of parameters indicating their values, standard errors, and how they were obtained; (2) diagrams or flow charts showing the logical structure of the model; and (3) the results of sensitivity analysis on key parameters.

1.4.4 Uncertainty and economy-wide modeling

Uncertainty is a common challenge in modeling and is not specific to GE. In all cases, the degree of uncertainty in a result should be characterized and reported. Parametric uncertainty in nonlinear models can be addressed via systematic sensitivity analysis, uncertainty propagation via Monte Carlo simulation, or the delta method. These methods are well-developed and are part of the set of best practices for all numerical computation, not only economy-wide modeling. They are appropriate for estimating the impacts of both statistical variability and of parameter uncertainty. The first two could also be used to address uncertainties related to exogenous data as well.

Sensitivity analysis, in particular, should be a routine part of all regulatory analysis using GE models. In addition, it can be used to compare alternative model formulations. As discussed in other parts of the report, model comparison projects similar to those run by the Energy Modeling Forum would be a valuable way to understand model uncertainty and to clarify the key sensitivities of model results to differences in model structure and parameterization.

A minor source of uncertainty and imprecision internal to a GE model is the convergence tolerance of its solution algorithm. Most models are solved using tolerances several orders of magnitude smaller than the main effects of relatively large policy experiments. In those calculations, convergence per se is not an issue. However, for policies causing extremely small price or quantity effects, model results should be tested to insure they are robust to tightening of the tolerance.

Because many model outcomes will not be normally distributed, where possible the overall degree of uncertainty in a result should be characterized by providing a confidence interval or a set of percentiles, such as the 5th, 25th, 50th, 75th, and 95th, for the variable. Where that is not possible, the mean and standard deviation should be reported. In the case of sensitivity analysis, upper and lower bounds should be reported for each outcome of interest.

1.4.5 Priorities for future research

EPA's top priorities for future research are issues that have come up repeatedly in the report. First, it should encourage further development of CGE models that can capture involuntary unemployment. In the near term the focus should be on frictional unemployment but over the longer run it should also include structural unemployment. Second, EPA should encourage far more inclusion of non-market benefits into economy-wide models. A particularly important aspect of this research should be to move away from the currently conventional practice of imposing separability between non-market benefits and market decisions. Third, EPA should encourage model developers to introduce explicit treatment of mortality risk into the utility functions used to represent households in order to reconcile economy-wide measures of equivalent variation with partial equilibrium measures of the willingness to pay for risk reductions. Fourth, EPA should encourage research on linking relatively aggregate GE models to more detailed models of households, industries or regions. The focus on this work should not be on linking per se (for which there is an extensive literature) but rather on understanding the inconsistencies that arise from linked rather than fully integrated models. Research on linking should be a near term priority. Fifth, EPA should convene a series of model comparison exercises for models of air regulations focusing on several key modeling issues. Sixth, EPA should be to encourage research on the impact of heterogeneity within regulated industries. Seventh, EPA should help establish an open-source project to assemble a freely-available database for use in CGE modeling.

2. INTRODUCTION

The National Center for Environmental Economics in the EPA Office of Policy requested advice from the SAB on the use of economy-wide modeling (EWM) for assessing the benefits and costs of air regulations. The agency's current approach uses detailed engineering-based compliance cost assessments (ECA) and partial equilibrium (PE) market models for estimating social costs, and PE models for estimating benefits as well. EPA asked the panel to: (1) evaluate the technical merits, methodological challenges, and potential value of using economy-wide models as a supplement to these tools; and (2) to suggest paths forward that would improve the usefulness of economy-wide models for regulatory analysis.

Economy-wide modeling is a very broad term encompassing several distinct approaches that will be discussed in subsequent sections of the report. However, a key characteristic of EWM is that it disaggregates the overall economy into a number of smaller units, or agents, that are each represented by an appropriate submodel. Some of these agents may be producing sectors, such as primary metals or motor vehicle manufacturing, and some may be different household groups, such as single-parent families in the Northeast. The agents interact through markets for goods and factors of production. For example, some of the output of the primary metals sector is sold to manufacturers of durable goods as an intermediate input; finished durables are sold to other firms or to households; and households supply labor to both primary metals producers and durable manufacturers.

The EWM approach that has been most widely used for environmental policy analysis is general equilibrium (GE) modeling. Pure GE models have two distinctive characteristics: (1) equilibrium prices that cause all markets to clear at all times; and (2) strict enforcement of all budget constraints faced by individual agents. In the body of the report we discuss a range of hybrid models that relax one or the other of these restrictions for some markets or agents. However, these characteristics are at the heart of the value added of EWM above and beyond ECA and PE analysis so for clarity we will generally refer to economy-wide models as GE models. When discussing computational rather than analytical models, we'll use the term CGE models.

GE modeling is a potential supplement to ECA, not an alternative to it. In most cases, benefit-cost analysis of a proposed regulation must begin with an engineering assessment that focuses on estimating "direct compliance expenditures from adopting a particular technology or process (i.e., capital costs, operating and maintenance costs, administrative costs) by an individual emitting unit or facility conditional on a given level of output" (USEPA 2015a). ECA is usually needed because the benefit-cost analysis must be done before the regulation takes effect and thus before the actual pattern of responses to the proposed new rules can be observed.[1] Typically it would identify key details regarding the options available to firms to comply with the regulation, including: alternative production technologies available; constraints on the use of particular technologies (for example, use of required equipment); and the cost-minimizing combination of operations that meet both the regulatory constraints and production goals.

In principle, GE modeling can make two contributions to the analysis of an air regulation beyond ECA and PE. First, the connections in GE models between markets throughout the economy can allow it to pick up effects that spill over from one market to another. For example, it would be possible to track the impact of a policy affecting fuel costs through to changes in the costs of energy-intensive goods like aluminum, and from there to the costs of products using aluminum, such as aircraft. Similarly, GE modeling can track the benefits of regulation through the economy as well. For example, reduced exposure to pollutants reduces morbidity and mortality, thereby potentially increasing labor supply. Higher labor supply keeps wages lower than they would otherwise be, reducing costs to labor-intensive industries.

A second benefit is that a CGE model provides a consistent and comprehensive accounting framework for adding up all the effects of a regulation while imposing budget constraints on all agents. Imposing budget constraints allows a CGE model to provide a useful reality check on the results from an ECA or PE. For example, a regulation that causes additional use of labor in one industry may bid up wages since that labor will usually need to be drawn out of competing sectors.

In practice, however, GE modeling can be challenging to apply. Most importantly, it imposes a formidable data requirement: since the approach is comprehensive, all sectors of the economy must be included in the model, at least in an aggregate form. Moreover, the data usually available to determine the parameters in GE models is often very coarse relative to the needs of the agency. For example, the best available time-series data on historical flows of intermediate goods between industries divides the entire US economy into several hundred sectors at best. However, air regulations often apply to very narrow production processes within subsectors of those industries. In addition, production processes may vary from one region to another (especially in old versus newer plants), and emissions may be highly localized, exposing narrow sectors of the population. As a result, it can be very challenging to map a detailed ECA for a

[1] The exception would be policies that mimic events for which there is a clear historical analog and thus statistical evidence on the reaction of regulated entities. An example would be broad-based energy taxes imposed at levels consistent with historical fluctuations in energy prices.

regulation into a set of appropriate inputs for a GE model. Finally, some consequences of regulations, especially short-term location-specific unemployment, are not included in most existing GE models. Together, these difficulties mean that GE modeling will not be suitable for analysis of some regulations.

As part of an effort to use the best available analysis for evaluating regulations, the EPA asked the SAB to evaluate 29 charge questions on the technical merits and challenges of economy-wide modeling. The questions were grouped into four broad categories: (1) measurement of social cost; (2) measurement of benefits; (3) evaluation of economic impacts; and (4) comparability and transparency. To support the evaluation, EPA provided a number of white papers and background documents discussing the literature and EPA's current practices for evaluating air regulations.

Seven of the charge questions fell in the first category: the strengths and weaknesses of GE models for evaluating the full social cost of regulations. The social cost differs from the direct compliance cost estimated in a CC analysis (and is usually larger) because it reflects the impact of the regulation on welfare. This is the area where GE models have been used most heavily for environmental policy analysis and the literature is most extensive. The agency provided two supporting documents: *Economy-Wide Modeling: Social Cost and Welfare White Paper* (USEPA 2015a); and *Memo on Using Other (Non-CGE) Economy-Wide Models to Estimate Social Cost of Air Regulation* (USEPA 2015c). The SAB was not charged with reviewing these or the other documents mentioned below.

The second category on the measurement of benefits consisted of eleven charge questions. GE analysis has been used less extensively for estimating environmental benefits than for social costs. The challenges are greater in some respects, including in the integration of PE and GE measures. The agency provided one supporting document: *Economy-Wide Modeling: Benefits of Air Quality Improvements White Paper* (USEPA 2015b).

Category three on economic impacts concerned distributional outcomes: how the benefits and costs of regulations are distributed across sectors and households. It included six questions and was supported by two documents: *Economy-Wide Modeling: Evaluating the Economic Impacts of Air Regulations* (USEPA 2016a); and *Economy-Wide Modeling: Use of CGE Models to Evaluate the Competitiveness Impacts of Air Regulations* (USEPA 2016c). The remaining category included five questions related to the comparability, transparency and reliability of GE models. It was supported by one document: *Economy-Wide Modeling: Uncertainty, Verification, and Validation* (USEPA 2016b).

In response to the EPA's request, the SAB convened an advisory panel on Economy-Wide Modeling of the Benefits and Costs of Environmental Regulation. The panel held a series of public meetings and teleconferences to deliberate on the charge questions on July 15, 2015, October 22-23, 2015, March 10, 2016, July 19-20, 2016, December 7, 2016 and May 24, 2017.

This report provides the findings and recommendations of the SAB in response to the charge questions (Appendix A).

Although some charge questions focus on specific features of existing economy-wide models, most are much broader and ask about the appropriateness of GE modeling as a methodology. Because it is a highly flexible approach there are few circumstances where it is categorically inappropriate: with enough data and development time, almost any feature could be incorporated. As a result, when responding to broad questions we will often discuss the appropriateness of GE modeling over the broad time periods below:

Possible now: What can reasonably be done very soon building on existing models and known datasets; roughly now through the next five years.

Near term: Modeling extensions that are high priority and possible over a somewhat longer period; roughly what could be developed, peer-reviewed and suitable for regulatory use in five to ten years.

Long term: What could be done over a longer period of time, either because the innovations require considerable development of the underlying theory or because new datasets would need to be assembled; roughly requiring ten years or more to be developed and thoroughly vetted.

Undesirable: Applications where GE modeling would not be useful, or research on new model features that would produce little analytical benefit relative to their cost and complexity.

3. MEASUREMENT OF SOCIAL COSTS

3.1. Advantages and Disadvantages of an Economy-Wide Approach

Charge Question: EPA has extensive experience using a wide range of economic models to evaluate air regulations. These models are generally tailored to the scope and timeframe of the regulations, ranging from static partial equilibrium models that estimate costs in a single product market in a single year, to dynamic CGE models that estimate costs for multiple markets over time. What are the advantages and drawbacks of a CGE approach (versus an engineering or partial equilibrium approach) for estimating social costs, including the differences in social costs between alternative regulatory options?

To frame the discussion of CGE models, we first consider two simpler approaches: (1) stopping the analysis after the engineering cost assessment (ECA) and treating the engineering costs as the social costs of the policy, or (2) augmenting the ECA with a partial equilibrium (PE) analysis.

By design, an ECA measures only the direct compliance costs of the firm, not any change in consumer surplus from reduced consumption of the end product. It does not measure consumer responsiveness to higher production costs passed on in terms of higher prices, or averting behavior by consumers, or substitution in consumption. Moreover, in calculating direct compliance costs an ECA usually assumes that input prices faced by firms are constant, which may not be true for policies causing large changes in the economy. If any of these impacts are significant, the true social cost of the policy may differ substantially from the engineering cost (see Hazilla and Kopp, 1990).

A partial equilibrium analysis extends an ECA by including more economic behavior of both firms and consumers in a particular market. A PE model may involve econometric estimation of a smooth marginal cost curve, which becomes the supply curve in a competitive market (or is the basis for calculating firm behavior in the case of imperfect competition). Econometric estimation of demand captures consumer behavior, and the interaction of supply and demand behaviors determines equilibrium quantity and price, along with producer and consumer surplus. The model can be used to simulate the effects of a policy change to get the new quantity, price, and surplus measures. By construction a PE model only captures effects on a limited number of markets (typically one, although multi-market PE analysis is sometimes used). However, a potential strength of the approach is its ability to incorporate a wide range of types of averting behavior, and thereby produce greater insight into possible unintended consequences and social costs of a regulation.

Those alternatives are frequently employed by EPA analysts who now contemplate more extensive use of computable general equilibrium (CGE) models. First-generation CGE models were often single-period models of one equilibrium year for a dozen or more industries that each use the other industries' outputs as intermediate inputs as well as primary inputs of labor and capital. A single year's data for all industries' inputs were used to calibrate production parameters, just as trade and other data were used to close the model. All competitive industries just break even, and payments to labor and capital are spent by consumers to maximize utility by purchasing those outputs. Again, the model can be used to simulate effects of a policy change on all new quantities, prices, and welfare. The main purpose of employing a CGE model is to capture feedback effects from one market to another: if a tax on one output raises its price, then consumers can switch their spending toward other outputs according to particular cross-price elasticities in a way that is consistent with budget constraints.

Those early CGE models have been followed by efforts to include additional features such as: labor-leisure choices by households; econometric estimation of flexible production and demand systems; recursive dynamic models with savings from one period used to augment capital in future periods; perfect foresight dynamic models that calculate all prices in all periods simultaneously; stochastic dynamic general equilibrium models; noncompetitive behavior by firms; and worldwide models of trade and factor flows between a dozen regions.

A possible disadvantage of the CGE approach is its relatively aggregated structure with less detail on each industry than offered by some engineering or partial equilibrium models. With additional programming resources, however, further model development has been undertaken to link CGE models and specific engineering models, in attempts to attain the advantages of both. A "soft link" can use the price outcomes of a CGE model in an engineering model to calculate new cost-minimizing operations. A "hard link" could iterate back and forth between the outcomes in a CGE model and outcomes in the engineering model until all those outcomes are consistent with each other. These approaches are discussed further in Section 3.6.

In the **near term** we recommend that EPA encourage efforts to incorporate an important additional feature into CGE models: involuntary unemployment. In the **long term**, as the literature on behavioral economics matures, we also recommend that EPA encourage integration of those insights into CGE models. For example, households appear to adopt energy efficiency technologies more slowly than would be expected from the apparent rates of return on those investments. In the long term, CGE models could be refined to capture that phenomenon. Because the methodology is very flexible, virtually any feature, such as those listed above, can be added with sufficient additional data, programming and computational resources.

Thus, we now face many differences *among* various CGE models, as well as differences among engineering models and partial equilibrium models. And of course some very useful analytical general equilibrium models can be as simple as a PE model, while still capturing the important interactions and budget consistency of general equilibrium analysis.

For all of these reasons, we caution against placing too much attention on the choice between a CGE approach versus the alternatives of an engineering or a PE approach, as posed in this question. The more important choices are among particular model features appropriate for the problem at hand. And a good approach may well involve a suite of different models. Different models might include any of the ten features listed above, for example, without trying to build a single multi-purpose model with an ever-growing number of features that make the model unwieldy to use, difficult to interpret, and opaque to uninitiated readers. In Section 3.7 we discuss an eclectic modeling approach that may be a useful alternative to CGE modeling for some regulations.

All that said, a few key principles can guide the necessary choice between engineering models, PE models, and CGE models. Clearly an engineering or PE model may well be sufficient for analysis of a policy in one market that is not expected to affect other markets throughout the economy, and consumer responsiveness to higher production costs, averting behavior, or substitution in consumption are not significant factors. We see two general and important arguments for using a CGE model:

1. A CGE model can capture important interactions between markets, if *both* of the following are present:

- Significant cross-price effects, where a costly policy in one market drives consumers to buy more of a substitute or less of a complement good from another industry, and
- Significant distortions in those other markets (e.g. market power, taxes, externalities, or regulation).

2. A CGE model can provide a consistent and comprehensive accounting framework to analyze and to combine effects of a policy change on the cost side and the benefit side in a way that satisfies all budget and resource constraints simultaneously.

- Especially in the case where improvements in environmental quality are not separable in utility but in fact affect demands for private goods which themselves may have welfare effects because of pre-existing market power, taxes, externalities, or regulation.
- Even in the case where environmental quality public goods are separable in utility (and the interactive effects described above do not arise), the consistent and comprehensive framework provided by a CGE model may be valuable.

We now turn to further discussion of these points. The best way to see the advantage of a CGE model described in the first point is to look at a simple expression derived from the analytical general equilibrium model of Arnold Harberger (Harberger, 1964), written before any CGE models were developed. He assumes constant marginal costs and linear demands (most valid for small changes). He thus calculates approximate changes in consumer surplus, while new-generation CGE models can calculate "exact" utility-based measures like an equivalent variation (see Section 3.5 below). Yet, his simple formula demonstrates clearly the key economic forces that operate in any recent CGE model. He considers *n* commodities, each of which might be affected by a per-unit excise tax, a costly regulation, or a price mark-up from monopoly power. Any one of these price wedges T_i (*i*=1,…*n*) can affect demand for any other commodity X_j through the cross-price term $S_{ij} \equiv \partial X_j / \partial T_i$. Ignoring any benefits from these taxes or regulations, the total social cost or "deadweight loss" (DWL) from price distortions is:

$$DWL = \frac{1}{2} \sum_i^n \sum_j^n S_{ij} T_i T_j \ .$$

where DWL<0 for a loss (social cost). The derivative of that DWL with respect to a small change in T_i is:

$$\frac{\partial DWL}{\partial T_i} = S_{ii} T_i + \sum_{j \neq i}^{n} S_{ji} T_j$$

The first term on the right-hand side of this expression is the direct effect on economic welfare from a change in tax or other price wedge in the i^{th} market, as would be captured perfectly effectively by a partial equilibrium model of that market alone. It is the addition or subtraction from the "Harberger Triangle" welfare cost of that tax. The second term is the sum of all general equilibrium effects of T_i in *other* markets. Each such general equilibrium (GE) effect is zero or negligible if either: (1) the cross-price effect on demand (S_{ji}) is zero or negligible, so that the policy in market *i* does not affect demand for good *j*, or (2) the market for good *j* has no existing tax or price wedge (T_j= 0). In other words, the policy in market *i* may have effects on demand in other markets, but those effects do not impact overall welfare unless and to the extent that the other market has a pre-existing distortion that is exacerbated or ameliorated by the change in T_i. Moreover, as shown by Carbone and Smith (2008), this analysis can be generalized to include nonseparable public goods and externalities, which can be shown to lead to distortions in resource allocation conceptually analogous to tax wedges.

The second term on the right-hand side of that expression can be ignored if *either* the cross-price effect is negligible *or* the price wedge is negligible. Thus the first point above says that a CGE model may not be necessary unless *both* the cross-price effect is significant *and* the other market has a significant price wedge arising from a distortion (e.g. market power, taxes, or environmental regulation). If those two conditions *are* met, then Harberger's formula itself provides a good approximation of the general equilibrium welfare effect for small changes, but the use of a CGE model can: (1) capture those general equilibrium effects, (2) calculate an exact measure of welfare instead of an approximation, (3) capture the effects of large changes and not just small changes, and (4) also incorporate other complications enumerated above.

The second point above is that a CGE model provides, in principle, a consistent and comprehensive accounting framework for adding up all the effects of a regulation including all costs and all benefits. However, we are concerned that the use of a CGE model that omits some of the costs or benefits may leave a misleading impression of net welfare effects due to incomplete accounting. Many of the benefits of air regulations are difficult to represent in a CGE model because of potentially non-separable ways that cleaner air may affect demands for private goods and services with pre-existing price wedges that affect welfare.[2] But leaving out those benefits entirely seems inappropriate; they could at least be modeled as a separable entry in utility to include all benefits in the same model until such time as research clarifies how to model the non-separable effects. Of course this short term solution implicitly assumes that the market goods are perfect substitutes for nonmarket environmental services. Although existing empirical data is inadequate for parameterizing a full range of environmental goods in CGE models, studies to date do suggest that perfect substitution is inappropriate in most PE applications. Moreover, we see no reason to omit benefits that are separable. That is, we have no *need* to include separable effects in utility under point 1 above, because changes in a separable public good have no effects on private goods or services with pre-existing price wedges. But these separable effects could be included anyway under point 2 above – to include all costs and all

[2] Changes in a non-separable environmental public good are not represented in equations above because those equations consider only n market commodities, but effects are analogous. For example, a change in air quality can affect demand for a market good X_j, with changes in welfare if that good has a pre-existing market distortion T_j.

benefits in a consistent and comprehensive accounting framework that respects all budget and resource constraints. A separate issue not addressed by these compromises is the incorporation of non-market feedback effects on regulations themselves. Large scale CGE models typically take policy settings as exogenous. Although policies cause changes in emissions, and thus in the externalities that motivate those policies, there is usually no feedback from changes in externalities to the stringency of the policy. Carbone and Smith [2008,2013] and Smith and Zhao [2016] have demonstrated in small CGE models this endogeneity can be important when calculating welfare changes.

Inclusion of resource and budget constraints in a CGE model allows it to provide a useful reality check in the analysis of policy. A CGE model specifies a labor endowment, for example, so any additional use of labor in one industry must come from somewhere else and may therefore bid up the economy-wide wage rate, whereas non-GE models often assume an infinitely elastic supply of labor. Another example is that total willingness to pay for separable public goods must fit within household budgets.

In evaluating the strengths of CGE models we note that a CGE model is emphatically not a forecasting model. Rather, it shows the consequences of a policy change under very specific circumstances: that all other economic conditions remain at values set in the model's baseline simulation. A proper forecast of all effects with a policy change would require forecasts of all the other changes in the economy as well – changes in population, income, growth, technology, trade, macroeconomic shocks, or discovery of new natural resource deposits. The purpose of a CGE model is essentially the opposite of a forecasting model; it asks what would be the effects of a particular policy change alone – with no other changes in any of those other variables. This heavy use of the "ceteris paribus" assumption allows it to isolate effects of the policy change alone and thereby to calculate the welfare effects of the policy without interference from other simultaneous changes in other variables.

This aspect of CGE models makes them difficult to validate using data on the aftermath of particular policy changes. The simulation of a policy change in a CGE model assumes no other changes, but any actual policy implementation is always accompanied by many other changes (in population, income, growth, technology, trade, macroeconomic shocks, or discovery of new natural resource deposits). The bottom line is that the simulation from a CGE model needs to be described carefully. It should not be said to "predict" or to "forecast" the effects of a policy. It is a counterfactual calculation of effects only for the policy change and nothing more.

3.2. Factors Affecting the Merits of an Economy-Wide Approach

Charge Question: Model choice and the appropriateness of using an economy-wide approach to evaluate the economic effects of policy are dependent on many factors. For example, a CGE model may be more appropriate for use in the analysis of a regulation that is implemented over several years and that constitutes a large-scale intervention in the economy, requiring relatively large compliance expenditures that impact multiple *sectors, either directly or indirectly. How does each factor listed below affect the technical merits of using an economy-wide model for estimating social costs? Please consider the relative importance of these factors separately.*

3.2.1 Relative magnitude of the abatement costs of the rule

To answer this question effectively one must clarify what the economic quantity is to which the magnitude of abatement cost is being compared. We take the important criteria to be whether the costs of pollution abatement are large relative to the value of the economy's aggregate factor income, and whether the target sector has strong backward and/or forward linkages with the rest of the economy.

To understand these qualifications it is instructive to consider abatement costs that are large relative to the output of a particular sector. If that sector has only minor linkages with the rest of the economy—both backward, accounting for a small fraction of the economy's utilization of intermediate goods or hiring of primary factors, and forward, selling a small fraction of its product to satisfy intermediate demands in downstream industries and/or final demands by consumers—then the bulk of the regulatory impact can be captured using a partial equilibrium model of the regulated sector.

Conversely, a sector with a large share of GDP or aggregate value added will by definition account for a significant fraction of the economy's hiring of productive factors, thus there will be feedbacks on factor prices and household income. All else equal, the larger the target sector's share of a particular factor, the larger the potential impact on the price of that factor, and the more important it is to capture those effects through a CGE analysis.

With that said, also note that there can be important reasons for using general equilibrium analysis even for small shocks. In particular, Goulder and Williams (2003) suggests that while the absolute error (i.e., how big the error is in dollars) caused by ignoring general-equilibrium effects grows as policy shocks get larger, relative error (i.e., how big the error is as a percentage of the estimate) goes the opposite direction: the relative error gets larger as policy shocks get smaller. Thus, if minimizing relative error is important, one should use economy-wide modeling even for small policy shocks.

In practical terms, the implicit precision of a CGE model will limit its ability to provide useful results for very small shocks.[3] The precision of the model's response to a given policy change will be limited by factors including: the precision of its parameter estimates; the precision of its exogenous inputs; the magnitudes of the statistical discrepancies in the input data (which is compiled from multiple and often inconsistent sources); the degree of aggregation used; rounding error in calculations and data storage; and convergence tolerances in the model's solution algorithm. Together, these factors contribute to confidence intervals for CGE results.

[3] See the glossary for an explanation of how the term "precision" is used in this document.

Small shocks may lead to point estimates that look meaningful but in fact are statistically indistinguishable from zero. The degree of aggregation is particularly important. For small shocks affecting a narrow component of a broad, highly aggregated sector, CGE models may add little insight or, worse, provide false precision: a careful sensitivity analysis would usually produce a range of possible outcomes that is wide compared to the magnitude of the shock (for example, by accounting for potential differences between the aggregate parameters used in the model and the subsector's true parameters). In contrast, a larger shock that would affect most of the firms in a given sector of a model would be a much better candidate for a CGE analysis.

For example, consider three regulations described in US EPA (2015a): Automobile and Light Duty Truck Surface Coating NESHAP; Portland Cement MACT; and Mercury and Air Toxics Standards (MATS) for power plants. The surface coating rule has relatively low compliance costs and applies to a segment of the economy that is much narrower than the corresponding sector of some CGE models. Analyzing it in a model where the activity would fall in a broad sector such as "durable manufacturing" or "energy-intensive manufacturing" would produce very imprecise results and CGE modeling would contribute little. CGE analysis would be more meaningful in a detailed model with a separate sector for motor vehicle manufacturing but the activity is still very small relative to the overall sector (roughly $150 million in an industry with revenues of $500 billion in 2007). Overall, the rule is not a good candidate for economy-wide analysis.

In contrast, MATS is a clear case where CGE analysis could be useful. It has compliance costs of almost $10 billion and it affects a large portion of an industry that has a broad impact on the economy and is usually modeled in detail. Although as noted in EPA (2015a) there remain challenges in developing an appropriate representation of the rule in a given CGE model, the significance of the rule and the fact that it aligns relatively well with the sectoral detail in many models means that it could be a candidate for economy-wide modelling.

The merit of CGE for the Portland cement rule is unclear. On one hand, the rule's compliance costs are considerably larger than the surface coating rule, and the industry is considerably smaller. It is thus likely to have a significant effect on the industry and on buyers downstream. However, few models disaggregate the economy down to a level that matches the industry and a CGE analysis might contribute very little of significance when the model's precision is considered. The decision on whether to carry out an economy-wide analysis should thus rest on whether a model with adequate sectoral detail is available (or a credible method for linking the CGE model to a more detailed sectoral model).

3.2.2. Time horizon for implementation of the rule

The time horizon for implementing a rule—that is, whether it is implemented quickly or gradually, and whether it is permanent or temporary—doesn't affect the value of a CGE analysis per se. Rather, that is determined by the considerations discussed in Section 3.1 including the connections between markets, the magnitude of existing distortions, and the need for consistency in the imposition of budget constraints. However, the time horizon can be an important consideration in the choice between types of CGE model. In particular, for all but quickly-implemented, temporary policies, dynamic models are preferable to single-period models. Dynamic models capture the evolution of the economy over time in response to (or in anticipation of) the policy. Single period models, however, can only capture the immediate short run equilibrium (if capital stocks are fixed) or the very long run equilibrium (if capital stocks are flexible but rates of return are fixed).

A key feature of dynamic economy-wide models is that they include modules that track important variables that evolve endogenously over time including capital stocks, savings, levels of public and private debt, and in some cases, the level of technology. There is thus a strong reason to use such models for analysis of polices that are likely to affect those variables. Partial equilibrium analysis of a policy that affects the cost of new capital goods, for example, will miss the impact of the policy on the evolution of the economy's capital stock and may understate the welfare cost of the policy significantly as a result.

With that in mind, the key issue is not so much the time horizon of the shock as much as the impact of the shock on intertemporal variables. Other things equal, a long-term shock that affects consumption may not be a high priority for economy-wide modeling: a partial equilibrium analysis for one year may adequately represent the impact in other years. However, even a short term shock that affects saving or investment would be a priority: examining the impact in early years alone will fail to capture the effects on future years.

In addition, economy-wide models are useful for capturing the economic consequences of rules that are progressively phased in. Some CGE models use a recursive dynamic modeling scheme in which a core single-period CGE model with fixed capital stocks is embedded within a dynamic process that updates factor endowments and technology parameters in a myopic fashion (in each period, agents in the economy expect the future to be similar to the present). For example, in some models capital accumulation is driven by an assumption that households have a fixed marginal propensity to save out of their income, resulting in a multi-sector Solow-Swan model. The trajectory of welfare impacts of the rule can then be computed based on the sequences of economic equilibria produced by the model

Other models include explicit foresight by some or all agents (also discussed in Section 3.2.5 below), and such models are particularly useful for analyzing policies that are anticipated in advance. Capital accumulation is driven by the interaction between: (1) consumption-savings decisions made by households; (2) investment decisions by firms based on forward-looking value maximization; (3) public sector borrowing; and (4) flows of international capital. With forward-looking behavior, imposition of pollution control costs in a future period may induce anticipatory changes in investment in advance of the regulations' entry into force. The extent of such changes, and how different the resulting time-path of the general equilibrium price vector might be relative to that simulated by a recursive dynamic model, depends on the magnitude of abatement costs, the degree of convexity in the cost of adjusting capital stocks, and the intertemporal rates of time preference and substitution.

Other things equal, economy-wide modeling is a priority for policies that could have significant impacts on private saving, government borrowing, the prices of capital goods, or international capital flows. For policies that affect those variables but which are phased in over time, the use of a model with foresight may be particularly important. A clear cut case where these features of economy-wide models are particularly important, and where EPA has had a long tradition of using such models, has been the analysis of climate policy. In general, CGE modeling could be particularly valuable for regulations that involve investments that are both: (1) large in absolute magnitude, thus potentially impacting national-level capital accumulation and growth, and (2) sufficiently concentrated in particular sectors that industry-level impacts on costs are not small compared to the precision of the model (as discussed in the previous section). Examples could include regulations in the category identified in EPA (2015a) as "Single Sector Emission Rate Limits" where costs are large, such as the MATS rule discussed above, or those in US EPA (2015a)'s "Regional or State-Implemented Emission Targets" such as the primary Ozone NAAQS, which has compliance costs of approximately $8 billion. Both are large in magnitude and cause a shift in investment from ordinary capital to pollution control devices. However, as discussed below in Section 3.2.4, analyzing either of these policies in a CGE model presents formidable challenges.

3.2.3. Number and types of sectors affected

> *Charge Question: Number and types of sector(s) directly and/or indirectly affected by the regulation, and the magnitude of these potential market effects.*

This is a key determinant of the appropriateness of economy-wide, in particular multi-sectoral CGE, models for regulatory impact analysis. As noted in Section 3.1, it is the regulated sector's forward and backward linkages that determined the impact of the regulation on output prices in the market for its products and factor prices in the market for sectoral inputs. In turn, these price changes are responsible for the ultimate impact of the regulation on households' consumption and welfare. Output prices have impacts through income and substitution effects while factor price changes influence income directly. Together they determine consumption and drive the welfare changes produced by a policy.

There is no hard and fast rule for the number or type of sectors affected that justify a CGE approach; rather, the considerations should be those in Section 3.1: whether there are strong cross-price effects between markets, and whether pre-existing distortions are present in those markets. With weak cross-price effects and small distortions, a multi-market partial equilibrium approach that calculates the overall impact of a regulation by simply summing the effects across the markets may be adequate. With that said, those conditions are restrictive and may not hold for a regulation that affects a broad swath of the economy. There is a prima facie case for economy-wide modeling for policies with wide impacts (as long as the impacts are not small relative to the precision of the model; see Section 3.2.1 above). The Ozone NAAQS, for example, might be appropriate but the National Emissions Standards for Stationary Internal Combustion Engines, with a compliance cost of about $100 million spread widely throughout the economy, would not be.

3.2.4. Level of detail needed to represent the costs of the rule

> *Charge Question: Is it credible to assume more aggregate model parameters used in CGE are valid for a subset of the industry? When is it important to include a detailed representation of a particular sector, such as the power sector? When is it important to include transition costs?*

Engineering-based PE models can be constructed in ways that include an incredible amount of process and pollution control detail regarding individual production lines within industry groupings that are quite narrow. However, what is often less clear is the consistency with which such models account for the linkages between such activities and the rest of the economy, in either product or input markets. By contrast, as noted above, the input-output tables and social accounting matrices (SAMs) used to parameterize CGE models have a high level of sectoral aggregation, leaving discrete industries or processes which may be the target of air pollution regulations bound up with other, potentially unregulated, activities. Finding an appropriate way to represent a narrowly targeted regulation in a high-level economy-wide model can thus be a very difficult challenge.

In some cases, it may be possible to build an economy-wide model that disaggregates the processes in question as sub-sectoral technology-specific production or cost functions within the CGE framework (discussed further in Section 3.6). Several papers have developed techniques to exploit different kinds of engineering data to achieve this disaggregation in a way that reconciles the descriptions of the technologies with the economic logic of the SAM (i.e., respecting the fundamental accounting rules of zero profit and market clearance at the sub-sectoral level). The challenge is the often considerable cost and time necessary to undertake the necessary disaggregation, parameterize the resulting benchmark model with discrete technology detail, and then debug the newly parameterized technology-rich model in response to the imposition of regulatory shocks. This state of affairs is slowly beginning to improve with releases of dedicated discrete technology databases that are constructed so as to be consistent with input-output accounts. Thus far, these databases exist only at the national level (e.g. the GTAP version 9 Power Database) and not at the regional level that may be of more interest to EPA. This approach—building a customized model with details on intra-sector production processes—is most promising for regulations that apply to significant portions of large sectors, such as the MATS rule for power plants.

Building a custom model with process-level detail may not be feasible for regulations that affect narrow production processes distributed widely throughout the economy, such as the Ozone NAAQS or the National Emissions Standards for Boilers cited in US EPA (2015a). As noted in

US EPA (2015a), the Ozone NAAQS is particularly challenging because EPA does not know for certain what state regulators will do to comply and thus has an unusually imprecise measure of likely compliance costs, and because many areas remain out of compliance. Any attempt to model the ozone standard in an economy-wide model will thus be rough at best: it will require the development of a set of reduced-form shocks to industry costs that can be scaled up and down to bound the impact of the rule. The resulting analysis would shed light on the potential importance (or lack thereof) of general equilibrium effects but would not yield a tightly-defined point estimate of the social cost.

Market and technical rigidities that impede the reallocation of factors in the presence of the regulation indicate transition costs that could be an important component of the overall compliance costs. Transition costs could include the capital adjustment costs that attend additional investment in pollution controls mandated by regulation, or the costs associated with labor reallocations (falling on either employers or employees). Furthermore, there may be important transition costs associated with regulated producers' substitution among discrete technology options that are not adequately captured by smooth sectoral production or cost functions of the type typically used in CGE models. In principle, transition costs are part of social costs and are thus desirable to include in an analysis. As a practical matter, however, it will be most important to include them when they are large relative to the long term cost of a policy and can be modeled with reasonable precision.

Modeling transition costs entails an increase in the structural complexity of the exercise. Considering the specific problem of representing those transition costs related to stranded assets (capital) that result from discrete production processes, for example, requires three characteristics in an analysis. First, it requires a model representation of not only the processes that are the likely targets of regulation, but also substitute technologies (presumably with different input proportions: especially the precursors of targeted air pollutants). These substitute technologies are dormant in the benchmark equilibrium but are activated endogenously and produce a quantity of output that is determined by the interaction of the regulatory stimulus and input prices. Second, the model must include imperfect malleability of capital, in the sense that some or all of the capital associated with polluting production processes is modeled as a technology-specific fixed factor, the return to which declines as a consequence of regulation. Third, the analysis must focus on pollution control or alternative technology mandates that impose upon the sector the opportunity costs of purchasing capital to allow the operation of discrete activities which attenuate the use of polluting inputs.

How to specify these opportunity costs within the model will depend on the model's structure. One approach is to model the pollution control/alternative technology as having a markup over and above the conventional technology's operating cost. In this way, mandating a shift toward the alternative technology increases the cost of production of the sector in question, with the expected knock-on general equilibrium effects. For this reason, the cost markups of alternative discrete technologies are a key engineering uncertainty that drives variation in the price, substitution and welfare impacts of a regulation. As is clear from this description, however, capturing these kinds of costs presents very formidable modeling and data requirements. It may be possible for rules with large compliance costs that fall on narrow and well-documented segments of the economy (such as electric power) but may be infeasible in other cases.

Capturing firm-side transition costs arising from changes in labor and capital inputs can be done in models using an adjustment cost specification for sector-specific investment in human or physical capital. Because firms have a strong incentive to minimize these costs, they will be most important for policies that cause large changes in the demand for capital or labor and that must be implemented quickly. The costs will be smaller, and thus lower priority for analysis, for policies that are phased in gradually over a long period of time, or for policies that are anticipated well in advance of implementation. Employee-side transition costs arising from the need to move from one employer to another are discussed further in Section 3.7.

3.2.5. Appropriate degree of foresight

Charge Question: When is it appropriate to use a recursive dynamic model or an intertemporally optimizing model? If only one type is available, to what degree can alternative foresight assumptions be approximated?

In intertemporal CGE modeling there is a clear computational tradeoff between: (1) the number of goods and sectors, as well as the extent of technological detail within sectors, and (2) the length and granularity of the time horizon that a model is capable of simulating. Thus, if the focus of the analysis requires a very high degree of specific sectoral or technology detail and doesn't involve significant anticipation of future policy changes, then it may be both necessary and sufficient to use a recursive dynamic CGE approach. However, as noted above such models cannot represent anticipatory investment dynamics in the run up to a regulation or for a regulation that is designed to change over time. And they can create problems for measuring the economic welfare effects of a policy. Models without intertemporal optimization implicitly create distortions in all intertemporal markets, and, depending on the policy in question and its interaction with the structure of the economy, those distortions can affect the measurement of the policy's welfare impacts in ways that are potentially large, difficult to diagnose ex ante, and may be misleading.

For example, intertemporal models that do not include forward-looking perfect foresight decisions can be problematic because they include an implicit distortion related to savings behavior. In a forward-looking setting, consumers equate the marginal utility of consumption through time – this feature results in consumption smoothing because anticipated shocks in consumption are smoothed out by altering savings. Agents also look ahead and change savings in anticipation of higher returns. In general, a strong theoretical case can be made for solving economic problems in a forward-looking manner. However, the tradeoff is that the model structure often must be simplified to make parameterization and solution feasible. Without perfect foresight, models need to make exogenous assumptions about a change in savings behavior over time, which can lead to distortions that increase with the time horizon on which the policy binds. For example, Babiker et al.'s (2009) comparison of intertemporal and recursive-dynamic versions of the same multi-region, multi-sector CGE model show that while imposing of a climate change stabilization policy induces similar sectoral and price behavior in the two versions, over a multi-decadal time horizon available to undertake cumulative emissions of greenhouse gases, global macroeconomic costs are substantially lower in the forward-looking version, since it enables multiple regions to substantially shift their consumption as an additional margin of adjustment to the policy.

To the extent that avoiding distortions in intertemporal markets is important, and these distortions are likely to be significant, an intertemporal CGE model would likely be more suitable. At the same time, it can be difficult to defend the assumption of perfect-foresight in a policy context because it requires that economic actors have perfect expectations and knowledge of all policies in all periods of time covered by a modeling exercise. While techniques exist to introduce into intertemporal CGE models imperfect foresight of the **onset** of a particular regulation, once the regulation is in place its subsequent time-path (in terms of stringency, scope and other characteristics) is by definition known to economic actors, who anticipate it perfectly. Generalizing this point, it is possible to simulate regulations that change over time as a "phased" or "rolling" sequence of shocks to the economy, where actors intertemporally optimize within each phase of the policy, but changes in the attributes of succeeding phases are not anticipated. The extent to which such more realistic "partial foresight" might bring the welfare effects simulated by an intertemporal CGE model into closer alignment with that of its recursive dynamic counterpart has not been rigorously studied. These considerations highlight the importance of the analyst's judgment and the nature of the policy in weighing these trade-offs to select the dynamic structure of a model that is appropriate to any particular application.

One way of addressing the dichotomy between relatively aggregate intertemporal models and more detailed PE models is via a top-down/bottom-up modeling framework which utilizes an intertemporal CGE model in conjunction with a partial equilibrium techno-economic model that embodies the desired engineering detail in target sectors. The CGE model simulates trajectories of prices and investment which are used as inputs to the engineering model, while the latter computes technology capacities and output supplies that are used by the CGE model as quasi-endowments. The two models are run in an alternating fashion, iterating until both their solutions converge. This approach, while attractive, requires substantial time and effort to calibrate the linked top-down/bottom-up modeling system. The credibility of results thus generated also hinges on the strength of the linkage between foresight of the policy's impacts by the agents within the regulated industry and consumption smoothing behavior by forward-looking actors in the rest of the economy, when interactions between the two entities, such as intersectoral factor reallocation and associated income effects, are likely to be uncertain. This is likely to be a particular concern in modeling mandates for regulated industries to invest in abatement capital that is sectorally immobile and otherwise non-productive, but whose general equilibrium effects may induce adjustment of productive capital in other sectors. For example, the fact that Babiker et al.'s (2009) intertemporal CGE model could only be solved by dropping the vintaged capital structure of its recursive-dynamic counterpart highlights the kind of tension between intra- and inter-period capital adjustments that linking models may run into. Linking models is discussed further in Section 3.6.

3.2.6. International, fiscal and primary factor closure

Charge Question: When is a detailed representation of the rest of the world important for estimates of social costs?

In its broadest sense, model closure refers to the accounting rules by which exogenous economic forces outside the scope of the model are assumed to interact with, and affect, the endogenous solution for the general equilibrium of the economy under consideration.

Trade is important because the U.S. economy is large and open. In a closed economy the reduction in output of a regulated sector constrains the supply of the good associated with that sector. The price of the commodity thus affected is typically bid up, which in turn induces adjustments in sectors' intermediate demands and households' final demands for that good. Representation of international trade in the model allows the reduction in domestic supply to be offset by imports of the good from abroad, which, all else equal, can dampen the price and demand adjustments necessary to achieve market clearance. Symmetrically, if the affected commodity is exported, the price effects of a supply constraint induced by regulation will affect foreign demand, the export revenues that accrue to export agents, and, ultimately, aggregate household income.

The degree to which these adjustments at the boundary of the domestic economy end up altering the general equilibrium price vector relative to that of a closed economy depends on the fractions of the regulated industry's gross output accounted for by imports and exports, the sector's share of the economy's total value of trade, the price elasticities of demand and supply for the relevant import and export goods, respectively, as well as the economy's openness to flows of financial and physical capital.

Structural assumptions regarding demands for imports may be important for policy assessment. In CGE models, and other empirical simulation models, demands for imported goods and services are usually represented by an Armington (1969) structure, which treats goods or services within the same sector sourced from the domestic market versus foreign markets as distinct, differentiated, goods that are imperfect substitutes. Alternative structures that rely on contemporary theories of firm-level differentiation have also been proposed for CGE analysis (e.g., Balistreri and Rutherford, 2012), and in the context of global-climate and commercial policy the alternative formulations are material to outcomes. In terms of structural choices for the EPA's economy-wide modeling efforts, it seems essential that some form of product differentiation be used to accommodate observed trade flows (which for most products are inconsistent with an assumption of perfect substitution). The Armington structure is an appropriate starting point for analysis. In some industries—in particular extractive industries and those that process the raw materials like Portland Cement, primary iron and steel, oil and gas extraction and petroleum refining—output may be sufficiently homogeneous that a Heckscher-Ohlin formulation is more appropriate, and this cannot be approximated by a large Armington elasticity in many cases.

Another consideration regarding the international-trade closure concerns the representation of foreign agents and production, which determines both the demand for US exports and the supply of potential imports. Global multi-region models include a full representation of each economy as they interact in international markets. This class of models is most appropriate when policy has important general-equilibrium impacts across regions. For example, the analysis of carbon leakage across policy alternatives requires a consideration of indirect international price impacts on production decisions in foreign economies. For other research questions, however, it may be more appropriate to consider a more detailed open-economy model of the U.S. alone, abstracting from a full representation of the foreign economies. In this context the rest of the world is represented through US-import-supply and US-export-demand schedules. These schedules would generally have finite elasticities, which is consistent with a large-open-economy formulation. Additional control over export responses is sometimes facilitated through a constant-elasticity-of-transformation production technology that differentiates the output of domestic firms between home and export markets. This class of single-country open-economy models has been effectively used by the U.S. International Trade Commission to analyze various import restraints, and seems a logical choice for most research questions that involve domestic environmental policy with limited international scope.

The trade structures mentioned above require a set of parameters that can be challenging to estimate. Product differentiation across domestic and foreign varieties, as in the Armington structure, requires measures of the substitution elasticities (and perhaps elasticities of transformation). Additional parameters are needed for more advanced theories that include firm-level differentiation and the competitive selection of heterogeneous firms. In a multi-region environment these parameters indirectly, but fully, characterize trade responses. In a large-open-economy formulation, however, additional data are needed to parameterize the import-supply and export-demand schedules. There is significant literature, and debate, regarding the parameterization of trade responses, and it is important to recognize the challenges and note resulting model sensitivities to imprecisely measured parameters.

From a macroeconomic perspective the treatment of international capital flows (the balance of payments) is an additional point to consider. Countries borrow from and lend to other countries through trade imbalances. A country that runs a trade surplus is accumulating claims on future imports (capital outflows), whereas a country that runs a trade deficit is borrowing against its future exports (capital inflows). For single-period models (which have difficulty justifying an observed trade imbalance) or non-forward-looking dynamic models (where capital inflows and outflows can create problems for welfare calculations), it is usually appropriate to make the simplest assumption of a fixed (in nominal terms) trade imbalance. In dynamic multi-region models there are additional options. Fully consistent intertemporal models with forward-looking agents optimizing over an infinite horizon can include capital flows that are consistent with interest-rate arbitrage (see McKibbin and Wilcoxen, 2013). Shocks will induce changes in the capital flows and thus stocks of debt that need to be paid back, or at a minimum serviced through the implied interest payments in perpetuity. Various restrictions on international capital flows, all the way down to a period-by-period balance of payments constraints, might be entertained in a dynamic context. It is worth noting, however, that intertemporal welfare calculations can be problematic with restrictions on capital flows, because these represent implicit benchmark distortions.

The discussion above largely addresses capital flows as a response to trade imbalances but causality can also run in the other direction. Policies that raise or lower rates of return on investments in the US will lead to capital inflows or outflows through portfolio arbitrage by international investors. For example, a policy reducing the rate of return on US assets will lead to capital outflows, a deterioration in US terms of trade, and a movement in the trade balance toward surplus. These effects can be particularly important for policies announced in advance: capital can flow into or out of the US in anticipation.

A final note of caution is warranted for single-country models. Assuming that the U.S. faces a fixed interest rate in international markets is analogous to assuming that the U.S. is a small open economy facing an infinite supply of capital at that interest rate. This is generally inappropriate, and care must be taken to accurately represent the global constraints related to the balance of payments. Further, because trade responses depend on balance-of-payment adjustments, the balance-of-payment formulation should be reconciled with the assumed trade elasticities.

Stepping back from the details, trade responses have importance beyond analysis of the economy-wide policy burdens. In the climate change mitigation literature, a voluminous body of work has arisen that attempts to quantify the optimal tariffs necessary to offset international leakage of greenhouse gas (GHG) emissions (and shore up output and capital returns in abating sectors) when a subset of countries pursues unilateral climate mitigation policies and GHGs are embodied in internationally traded commodities. Studies have found that the welfare costs of such border carbon adjustments can be substantial, especially relative to alternative policies. To the extent that the regulations envisaged in the charge might involve technology mandates packaged with offsetting measures such as border adjustments, it will be important to evaluate the welfare impacts of each component as well as the total package. That is something that only a CGE model can do.

Another aspect of model closure that deserves mention is endogenous adjustments in factor supplies; that is, endogenous supplies of labor and capital. In single- or multi-sector partial equilibrium models the typical representation of the factor market assumes infinitely elastic supply at constant marginal cost. That is, changes in factor demands occurring in the sector are assumed to have no influence on the rest of the economy. It is straightforward to represent spillover effects on the broader factor market by introducing elastic factor supplies. However, what this misses is the feedback effect on household incomes and the potential knock-on downstream impact on the demand curve for the sector's output. Nowhere is this more important than household labor-leisure choice, which endogenously determines the adjustment of labor participation and hours in response to changes in relative prices. Capturing these effects is a key strength of economy-wide modeling.

Taking this point further, the vast double-dividend/tax-interaction literature looks at how general equilibrium interactions between government policy changes and pre-existing distortionary taxes can substantially change the economic costs of policy. This points to the importance of accounting for such interactions when measuring economy-wide costs (as noted in Section 3.1), especially when policy affects factors of production that exhibit some degree of price elasticity of supply (e.g., labor inputs when households can use their time for work or leisure). But this highlights yet another aspect of closure, namely assumptions regarding the government's budgetary balance and fiscal components of regulations that are price-based and generate substantial tax revenue. These assumptions have been shown to be quite important for a wide range of policy cases, from economy-wide taxation of GHG emissions to more narrowly targeted regulations that primarily involve pollution control mandates.

3.2.7. Availability and cost of economy-wide models

Charge Question: Please comment on the availability and cost of an economy-wide model versus alternative modeling approaches (i.e., to inform analytic choices that weigh the value of information obtained against analytic expenditures when resources are constrained).

A good way to approach the choice of model is to consider four possible options for any given analysis: (1) develop a new CGE model, or adapt an existing one, when no appropriate model is currently available; (2) use an existing CGE model having appropriate features; (3) use a small analytic general equilibrium model to capture economy-wide tradeoffs with less detail than a full CGE model would provide; and (4) to omit economy-wide analysis and focus on partial equilibrium or engineering analysis alone. These four options provide different degrees of benefit but also differ dramatically in cost and, as a result, may be appropriate in different circumstances.

Options 1 and 2 are attractive because the singular advantage of CGE modeling relative to other analytical approaches lies in the economic logic of the general equilibrium framework, in particular its ability to enforce a consistent accounting of the factors responsible for determining the economy-wide costs of a regulation, and thereby discipline the entire regulatory impact analysis exercise. Properly conducted, CGE modeling is thereby capable of providing the most transparent and rigorous way to track the economy-wide costs of regulation, and is the only way to consistently estimate aggregate welfare impacts. However, because the cost of developing a CGE model (including data collection, data validation and parameterization) is very high compared to the marginal cost of running an analysis, option 1 (building a model) should only be used when: (1) general equilibrium effects are expected to be large, (2) adequate data are available to parameterize the model credibly at the level of detail needed for the analysis; and (3) the model will be flexible enough to be used for multiple analyses. In contrast, option 2 (use an existing model) would be less expensive and thus appropriate for regulations where general equilibrium effects are smaller or where the modeling of the rule will need to be imprecise given its characteristics (e.g., as discussed above for the Ozone NAAQS).

When no appropriate model is available and the regulation in question doesn't warrant the development of a new model, option 3 (an analytical model) may be appropriate. Such models are often used in macroeconomics, international trade, and public finance. Small, stylized "back of the envelope" models also have a long history in CGE analysis for use in explaining the key mechanisms behind CGE results (see Dixon and Rimmer, 2013). However, building a small model that is suitable for a given analysis and will stand up to scrutiny is not a trivial task. If it is unlikely that significant costs will be omitted from a partial equilibrium analysis, then option 4 (omitting general equilibrium analysis) would be appropriate.

3.2.8. Ability to incorporate uncertainty

Charge Question: Please comment on the ability to incorporate and appropriately characterize uncertainty in key parameters and inputs (e.g., engineering costs)

Uncertainty is inherent to all models. They all depend on imprecisely-determined parameters and uncertain input variables. However, because the number of parameters in a typical economy-wide model is large, characterizing uncertainty in a transparent and systematic way is particularly important.

Although it is not often done, statistical uncertainty in CGE results can be characterized just as other econometric results are: by computing confidence intervals derived from the covariance matrices of their parameter estimates (see Jorgenson, et al., 2013b). Introducing engineering costs or other calibrated parameters into such a calculation is straightforward when the statistical uncertainty in those parameters is known. When it is not, it will usually be necessary to fall back to sensitivity analysis. Sensitivity analysis can identify parameters that have an important impact on variables of interest but it cannot be used to make probability statements about results, and it often does not take account of correlations between parameter estimates.

In applying economy-wide modeling to air regulations, it will be important to report sensitivity analysis, and confidence intervals when possible, for an analysis. Thus, the ability to incorporate and characterize uncertainty in parameters should be a key modeling requirement. Appropriate practices for characterizing uncertainty are discussed in detail in Section 6.4.

3.3. Other Factors to be Considered

Charge Question: Are other factors beyond those listed above relevant to consider when assessing whether and how to model the social costs of a regulatory action in an economy-wide framework?

Several additional factors other than those highlighted in the charge deserve careful attention. These issues range from the generic (information quality with respect to data, models and results) to the specific (data that are appropriate for use in an economy-wide model, labor transition costs, and structural complexity).

3.3.1. Information quality

Data

Government-wide information quality standards were established in 2002 pursuant to a statutory directive to the Office of Management and Budget (OMB 2002, 2005) which EPA has adopted U.S. EPA 2002). These standards apply to all information disseminated by government agencies, and they are increasingly stringent for information that is “influential” (potential effects could exceed $100 million in any one year) or “highly influential” (potential effects could exceed $500 million). An economy wide model meets the definition of “information,” and it presumably is either “influential” or “highly influential.”

EPA guidance (U.S. EPA 2008, 2015c) links information quality to peer review but does not always explicitly include a review of information quality as one of the scientific or technical issues listed in a peer review charge. Thus, peer review alone may not be sufficient to ensure that information quality standards are met. See Section 4.7.3 for a relevant example involving the Advisory Council for Clean Air Act Compliance and CGE modeling.

It is generally assumed that data used to populate PE or CGE models are fixed (i.e., without variability or uncertainty), unbiased, included without excess precision, and appropriate for their use. These assumptions are not unique to CGE models, of course. However, economy-wide modeling presupposes a desire for and commitment to greater accuracy, reliability and precision, not complexity for its own sake. Moreover, economy-wide modeling entails a dramatic expansion in the quantity of data that are needed and utilized. Therefore, it is especially important that full adherence to information quality standards be comprehensively documented before data are selected to populate an economy wide model.

Models

Model validation and reliability for policy decisions are key additional considerations. This is an area of limited research. While other methods of analysis (econometric models) have built-in, well established, indicators of statistical validity, many CGE models are constructed using data sets having limited time spans and may be saturated in terms of the number of parameters relative to the information provided by the data (discussed in more detail below). This makes validation challenging.

Both parametric and structural sensitivity are important considerations. The goal remains the provision of unbiased and reliable analysis of policy in an environment with very limited information. The advantage of a CGE approach is that it provides a structured mapping of assumptions to outcomes. At a minimum, an understanding of how the policy impacts are sensitive to specific structural and parametric assumptions is indispensable in quality policy analysis. To the degree that EPA adopts economy-wide models for analysis, an acknowledgement and understanding of the inherent sensitivities should accompany the central results and conclusions.

Proprietary data and models

Proprietary data and models generally cannot satisfy applicable information quality standards for procedural transparency because they are not capable of being reproduced by qualified third parties. Other EPA guidance requires that third-party information be independently verified and validated in the same manner as if the Agency had produced it (U.S. EPA, 2003), a standard that proprietary models generally cannot meet.

Additional clarity about the definition of *proprietary* models and the rationale for choosing between proprietary and nonproprietary models is useful here. Guidance issued by EPA in 2009 defines *proprietary models* "as those computer models for which the source code is not universally shared" (U.S. EPA Office of the Science Advisor Council for Regulatory Environmental Modeling 2009, p. 31). This definition is strict with respect to its domain and ambiguous with respect to its application. The definition is strict because it is limited to source code even though other model components may be equally or more important. But it also is ambiguous because the meaning of "universally shared" is not clear. In addition, though the definition is presented as evidence of the Agency's preference for nonproprietary models, the text establishes a safe harbor that protects proprietary models from competition. Proprietary models are preferred if they "provide the most reliable and best-accepted characterization of a system." The key interpretive terms "reliability" and "best-accepted" are not defined, and no criteria are given that would establish the conditions in which a nonproprietary model would be unambiguously preferred. A 2003 draft of this EPA guidance was the reviewed by an SAB panel (the Regulatory Environmental Modeling [REM] Guidance Review Panel), but no insight can be gleaned from that review. In its charge the Panel was not asked to address proprietary models, and the Panel's report shows that it did not deliberate on the matter (U.S. Environmental Protection Agency Science Advisory Board, 2006, pp. 5-7)

Meanwhile, a committee of the National Research Council (NRC) specifically addressed proprietary models in its EPA-sponsored review of environmental modeling (NRC 2007). The

NRC Committee reviewed EPA's 2003 proposed definition and rationale, and rejected both. It adopted a definition of proprietary models that is much broader in scope:

> A model is proprietary if *any component that is a fundamental part of the model's structure or functionality is not available for free to the general public* (NRC 2007, p. 184, emphasis added).

The NRC definition explicitly includes source code, third-party software, <u>and input data</u> (NRC 2007, p. 186).

The NRC Committee also recommended a fundamentally different rationale for choosing between proprietary and nonproprietary models, recognizing that both industry and environmental stakeholders believe "[p]roprietary models … are directly at odds with the goals of open government and transparency" (NRC 2007, p. 184). The Committee acknowledged that model developers might want to maintain the proprietary nature of their models, most notably, to retain the ability to earn financial profit (NRC 2007, pp. 184-185). But the Committee specifically noted that protecting the intellectual property interests of modelers likely would impede independent evaluation and deter innovation:

> The best way for a modeler to protect his intellectual investment in a model is to claim trade-secret protection. Protection is immediate and is accomplished by insisting that the model and its contents are secret. There are two main difficulties in evaluating the legitimacy of a trade-secret claim on proprietary models in terms of whether it ultimately serves the public interest. First, the owner of the proprietary information has the best information concerning whether there is a legitimate competitive advantage to keeping the information secret, thus, making it hard for outsiders to evaluate, especially if the owner has other, overlapping reasons to insist on confidentiality (such as to avoid controversy over assumptions and to retain control over the running of the model). Second, it is difficult to evaluate empirically whether providing secrecy to model developers will spur innovation. In other words, would modelers still develop models for the marketplace with private dollars, even without trade-secret protections? (NRC 2007, p. 185).

The NRC Committee recommended that EPA adopt a much stronger preference for nonproprietary models than the version the Agency proposed in 2003 (and subsequently finalized in 2009):

> The committee recommends that EPA adopt a preference for nonproprietary software for environmental modeling. When developing a model, EPA should establish and pursue a goal of not using proprietary elements. It should only adopt proprietary models when a clear and well-documented case has been made that the advantages of using such models outweigh the costs in lower credibility and transparency that accompanies reliance on

> proprietary models. Furthermore, proprietary models should be subject to rigorous quality requirements and to peer review that is equivalent to peer review for public models. If necessary, nondisclosure agreements could be used for experts to perform a thorough review of the proprietary portions of the model (NRC 2007, pp. 188-189).

This rationale avoids creating a safe harbor for proprietary models and ensures that the burden of proof for using a proprietary model is always placed on its proponents.

Substantively, we prefer both the NRC Committee's definition of proprietary models and its rationale for choosing between proprietary and nonproprietary models. Procedurally, the NRC Committee appears to have conducted a more comprehensive review of the issues. We would have considered an EPA rebuttal of the NRC Committee report, but no such rebuttal appears in the Agency's 2009 guidance even though the Committee report is frequently cited on other matters.

Model outputs

Like data and models, the outputs of economy-wide modeling are subject to information quality standards. Procedurally, results must be capable of being reproduced by qualified third parties. This means access must be provided on request, including comprehensive model documentation and computer code. Substantively, results must be objective (i.e., unbiased), protected from manipulation and interference for any reason (including policy reasons), and appropriate for their intended purpose.

3.3.2. Availability of appropriate data

A closely related issue which arises throughout this report is the level of aggregation of an economy-wide model in terms of industries, households and regions. Highly disaggregated models can allow regulations to be represented more accurately, improving calculations of social costs and benefits and providing greater distributional detail as well. In the early years of CGE modeling the level of detail in most models was constrained by computing power. As computing costs have fallen, however, the fundamental constraint on disaggregation has become availability of appropriate historical data for use in parameterizing a model. Greater disaggregation means a larger number of behavioral parameters and thus imposes greater demands on data collection. Inadequate attention to parameterization will undermine the validity of an analysis so it will be important for EPA to refrain from trying to use or develop models with greater disaggregation than can be credibly supported by existing data.

For example, the underlying data on intermediate inputs used to parameterize the production side of CGE models of the US ultimately comes from input-output data compiled by the US Bureau of Economic Analysis (BEA). BEA's data are available annually at a level of aggregation roughly equivalent to the 2-3 digit level of the North American Industry Classification System (NAICS). There are 40-70 sectors (depending on the year) and they can be relatively coarse for the purposes of air regulation. For example, BEA sector 331 is primary metals which includes all of the following: steel mills, manufacturing of steel products, alumina refining, aluminum product manufacturing, primary smelting of copper, and a range of additional activities. As a result, these data alone are insufficient for parameterizing a model with, for example, separate production sectors for steel and aluminum. BEA does publish more detailed benchmark input-output data corresponding roughly to the 5-6 digit NAICS level, which includes 300-400 sectors and distinguishes between the primary metals subsectors mentioned above. However, they are available only every five years. Model builders thus face a tradeoff between sectoral detail and the number of observations available for parameterization. To bridge the gap the US Bureau of Labor Statistics (BLS) uses the two levels of BEA data plus additional annual data and a set of assumptions and statistical techniques to construct an intermediate-level set of annual tables with about 200 sectors. Still, the sectors remain broad relative to the scale of many air regulations. BEA sector 47, cement and concrete product manufacturing, for example, is broad relative to sector-level emissions rules affecting Portland cement manufacturing. Even fewer data are available on production at a regional level in the US so building a model with high degrees of both sectoral and regional data is even more challenging.

Thus, the availability of data on production is a very significant factor to consider in determining when it is appropriate to use economy-wide modeling. An analysis that requires a high degree of sectoral detail may only be possible in a model that uses parameters determined with very few degrees of freedom. That, in turn, can limit the flexibility of functional forms used for modeling behavior. In short, given the underlying data available on production, it is not possible to have a model that is simultaneously: (1) highly disaggregated; (2) based on flexible functional forms; and (3) parameterized with a large number of degrees of freedom.

3.3.3. Representation of labor transition costs

Transition costs in the labor market, which will be discussed in detail in Section 5 on impacts, can potentially contribute to overall social costs as well. Suppose EPA believes that a proposed regulation is likely to contract some parts of an industry, thus leading to layoffs. A large empirical literature addresses the impact of layoffs on prime-aged workers. For example, Davis and von Wachter (2011) find that when such a worker loses his job, he suffers a protracted decline in labor earnings. In present value terms, a worker loses 1.4 years of earnings when he is laid off during a period with low unemployment and twice as much when he is laid off during a period when the unemployment rate is above 8%. Although this research does not exclusively look at layoffs due to regulatory changes, there is no particular reason to think that foregone earnings are likely to be significantly higher or lower in such cases. To the extent that the earnings loss represents a net social cost (as opposed to a purely distributional effect), that cost would be omitted by any model that ignores labor transition costs (see Kuminoff, Schoellman and Timmins, 2015). Such costs are discussed in more detail in Section 5.5.

To capture these costs in a CGE model would require a dynamic model that generates large and persistent earnings losses following a layoff. Some CGE models are moving in that direction (e.g., Hafstead and Williams, 2016), and as noted in section 3.1 we recommend that a near term priority for EPA should be to encourage further development of CGE models with involuntary unemployment. However, such models will be the first step in a longer term process: to fully capture these losses would require a very fine-grained submodel of the labor market, distinguishing between workers by occupation, industry and region, as well as requiring parameter estimates for the rate at which laid off workers move between jobs. jobs. Employment aspects of economy-wide modeling are discussed in more detail in Sections 5.4 and 5.5 of this report.

3.3.4. Structural complexity

Structural assumptions and computational complexity can bedevil the best analyst. For example, high-resolution long-time-horizon perfect-foresight models can be difficult to solve, and are quite difficult to validate due to the difficulty of observing the expectations of agents in the economy. Otherwise large models can be difficult to deal with in terms of being useful as an operational tool. The problems inherent in large models are as mundane as long solution times (and frustrating debugging cycles), or as fundamental as being unable to give an intuitive explanation of outcomes. Models require some degree of parsimony. In adding features like spatial resolution or multiple households we can inform distributional questions, but the communication of aggregate (representative agent) welfare impacts becomes more difficult. Good economic analysis finds the right balance of parsimony and complexity. Flexibility to include or exclude features depending on the research question is a good strategy. EPA should consider the benefits and costs of model complexity and try to strike the right balance for the question at hand.

3.3.5. Model choices

Below we list a number of model choices that are important considerations in the assessment of the social costs of regulation. The key to credible analysis is to highlight the choice over alternatives and to appropriately acknowledge any limitations. A useful economy-wide analysis will not necessarily include every detail or every current innovation in the model, but should consider the limitations of simplifying assumptions.

1. As noted above, the model's level of disaggregation should be appropriate given the data available to determine its behavioral parameters. This is something that is **possible now** with the appropriate development of flexible upstream data development tools.
2. As discussed in Section 3.2.5, an important model choice is the assumption about the agent's planning horizon in terms of the degree of intertemporal foresight. As a long-term strategy, it is important to have the flexibility to look at different planning horizons,

including the development of capabilities in perfect-foresight models. In the **near term** it is more important to consider the interpretation of comparative static results.

3. Some contemporary models consider imperfect competition—potentially an important consideration in regulatory policy. Building near to longer term capabilities in this area will keep EPA research closer to the forefront of methodological developments, adding credibility to applied models.
4. As noted in Section 3.1, existing distortions (i.e., existing taxes, subsidies, imperfect competition, and fiscal reactions to policy) are important and the choice to abstract from (or simplify) their representation can impact the analysis. This is an important research focus that is **possible now** but will be limited by data availability. Sensitivity analysis over the existence and quantitative nature of existing distortions is current good practice and should be incorporated into current work plans.
5. Theory suggests that there may be important endogenous impacts of policy on productivity growth and technological change. Modeling these explicitly can be challenging, but they should be considered. Incorporating these as an integrated part of an applied model is more of long-term priority, but current analysis should acknowledge these potential impacts.
6. Extensions that consider interregional or international factor movements can lead to significant complications, but spatial price changes will indicate migratory pressures that can be qualitatively recognized. Extensions in this area are a longer term priority. In the **near term** a presentation of the prices that indicate the incentives for factor movements is likely sufficient in a typical applied model. As policy makers focus on regional outcomes (e.g., employment and income), however, the value of model developments that include factor movements becomes more important.
7. The choice to incorporate subnational social accounts is useful in reporting spatial impacts, but the data are suspect because they are often based on apportioning national benchmark accounts in a way that diminishes the targeted spatial heterogeneity. Any time subnational accounts are employed it is important to undertake systematic verification and validation of the data for the key industries and commodities impacted by regulation.
8. Regulation will have public finance implications and interactions, and this opens up additional modeling choices regarding the instruments that control the size of the government and potential interactions with other parts of the economy. Sensitivity analysis over these choices is **possible now** and would be useful in any report. In intertemporal models, however, there is a longer term issue with respect to the benchmark evolution of government debt. A transparent standard treatment of the benchmark debt evolution should be established, but longer term alternative treatments might be explored.

This list is not intended to be exhaustive, but rather highlights certain considerations in modeling relevant policy questions. It is important to maintain and foster a close connection with others engaged with similar research questions. To this end, and as discussed in more detail in Section

6.3, the principles of data and model availability for peer review are critical for credible analysis. Continued participation of EPA analysts in professional meetings and peer-reviewed publications will be important in keeping EPA analysts in touch with the modeling community. Many of the important considerations for assessing whether and how to model the social costs of regulation in an economy-wide framework can be revealed through interactions with other experts through the professional forums.

3.4. Challenges in Modeling Regulations

Charge Question: Most EPA regulations do not operate through price; instead they are typically emission-rate and/or technology-based standards. What are the particular challenges to representing regulations that are not directly implemented through price in an economy-wide framework? Under what circumstances is it particularly challenging to accurately represent such regulations in these models relative to representing them in other modeling frameworks?

The more spatially, sectorally, and/or temporally detailed the regulation, the more challenging it is to represent in a modeling framework. For example, the National Ambient Air Quality Standards (NAAQS) are determined at the national level, with implementation occurring at the state level in accordance with air basin-specific considerations. As a result, the implementation of the standard can vary widely across air basins, making it difficult to capture in an economy-wide model, which usually are too spatially and sectorally aggregate to capture air basin-specific regulations. It is also difficult to predict what each state will do to comply with the NAAQS, particularly those compliance actions states must take that are not attributable to specific control measures and may cost more than EPA's upper-bound action.

Additionally, economy-wide models that explicitly or implicitly assume least-cost compliance strategies do not typically account for a number of rigidities in the real-world selection of compliance methods. Decision-making by regulated entities rarely, if ever, strictly follows the economic model of cost-minimization. There are numerous reasons for this, including:

- limited capacity to determine the cost-minimizing compliance strategy; few regulated entities have sophisticated models and compliance staff at their disposal to identify cost-minimizing compliance strategies
- endogenous constraints, such as competing business objectives, firm culture, stockholder and managerial interests, collective bargaining agreements, contracts with suppliers and customers, etc.
- exogenous constraints, such as societal norms, state/local conditions, civil and product liability risks, other regulatory requirements (imposed by the same or another agency), procedural requirements (e.g., federal, state and local permitting procedures; interactions with procedures of other regulators), etc.

Where appropriate data are available, **long term** development of economy-wide models should move toward accounting for any such constraint that would have a significant effect on output. In the **near term**, economy-wide analysis should note that these constraints are not included.

If a dominant compliance option is prescribed (e.g., via a technology-based standard, or a performance-based standard that has only one qualifying technology), the analysis should recognize the potential for monopoly power among suppliers of the technology. Unfortunately, most economy-wide models assume perfect competition or are too highly aggregated to capture these effects.

The degree of compliance and the potential importance of over-compliance may matter given nonlinearities in abatement cost functions, making abatement more difficult to model. There also exists the potential for non-compliance; for example, in the case of the NAAQS where air basins are trying to get close to the standard but are not able to achieve it.

One approach to modeling non-price regulations that has often been used in the literature is to treat them as adverse shocks to the productivity of the regulated industries. Engineering data or other information on direct compliance costs are expressed as a fraction of overall costs in the industry without the regulation. The regulation is then simulated by introducing a corresponding productivity deterioration in the industry (or an improvement in productivity for a counterfactual analysis of historical regulation). The deterioration is often Hicks-neutral and equivalent to assuming that the industry's compliance activities require the same mix of inputs as its ordinary production. However, when detailed information is available about the inputs required for abatement, factor-specific productivity impacts can be used. The factor-specific approach has been used for regulations in which the largest expense was pollution abatement capital. Either approach should be regarded as a first-order approximation, however, because both make strong simplifying assumptions about how firms comply.

It is also possible that non-price regulations could be modeled as their price-equivalents, using tax and subsidy combinations. (See, for example, Goulder, Haefsted, and Williams [2016]). However, there are potential challenges associated with implementing this approach—although these challenges also exist when modeling quantity instruments as well; for instance, how to identify what should be taxed when it is not always clear which sectors will be affected and by how much; how to implement the tax when there may be changes to the input process in response to the regulation; how to treat the timing of shifts in input responses. In order to implement the non-price regulation as a price-equivalent regulation, detailed price representation in the model is required, as detailed as the regulation itself. This raises the question of how many price margins can be incorporated into a model, and what matters most with respect to their representation. In addition, technology standards will constrain choices that will have welfare implications that are not captured with a price instrument.

For some regulations, EPA may have already identified the specific technology it expects industry to use to comply with the regulation. Introducing this information into an economy-wide model that doesn't have the same industry structure or representation as used in the engineering analysis can be challenging. If necessary, an approach linking the economy-wide model to a detailed sectoral model, as discussed in Section 3.6, may be appropriate. More granularity may also be needed in economy-wide models to represent other kinds of regulation. For example, in the case of CAFE standards, distinguishing between light trucks and passenger cars is critical. However, the importance of this level of detail is not unique to economy-wide models. Engineering analysis, for example, never accounted for the large cross-elasticity of substitution between light trucks and passenger cars. A strength of CGE models is that they remind the analyst that such elasticities are needed since accounting for substitution between products in nearby markets is core aspect of the methodology.

The challenge is incorporating all the relevant margins on which producers or consumers can adjust behavior in response to a specific regulation. In the case of CAFE under the rule's original formulation, each manufacturer had to comply on its own and compliance meant changing the mix of vehicles by selling more small cars and fewer large cars. However, the impact of the rule on overall fuel consumption was also affected by consumer behavior since drivers of higher-efficiency vehicles faced lower costs of driving. Each of these decision margins creates an additional Harberger loss triangle, so that the social cost of a regulation is likely to be underestimated in direct relation to the decision margins that are ignored.

3.5. Appropriate Metrics for Social Costs

Charge Question: EPA has previously used CGE models to estimate the social costs of regulation by calculating equivalent variation (EV) but has also reported changes in other aggregate measures such as GDP and household consumption. Setting aside benefits for the moment, what are the appropriate metrics to measure social costs? What are the advantages or drawbacks of using an EV measure vs. GDP or household consumption to approximate a change in welfare?

Regulatory policy affects people through changes in utility, either in their role as consumers facing higher costs of goods and services, in their role as workers or business owners through changes to their factor returns, or through restrictions on behavior (municipal or state bans on backyard leaf burning, as a concrete example). Whether focused on the consumer or producer side impacts of regulations, the burden (or social cost) of regulation falls on individuals and is manifested as a change in their well-being (generally measured by economists by use of a utility function of both market and non-market goods).

A utility function is a useful construct in economics but cannot be used directly to measure the social cost of policy in ways that allow comparison across individuals or in comparison to the benefits of regulation. Instead, economists use measures such as *equivalent variation (EV)* or *compensating variation (CV)*. EV and CV are money-based measures of a policy change. In the response to this question, we will focus on EV measures, as they are more typically used in policy assessment. Conceptually, EV is the maximal amount of money an individual would be willing to give up in lieu of some policy change (in the context of this question, a new or changed regulation). This benefit concept is a measure of the money equivalent to the total impact of the regulation (including changes in consumer prices, changes in wages or returns to capital, or restrictions on behavior).[4] This measure has a long history of use in economics dating back to Hicks (1939) and is an essential tool taught in both undergraduate and graduate level microeconomics. See, for example, Mas-Colell, Whinston & Green (1995).

While the question refers to the use of EV in CGE models, it is important to recognize that EV can be used in PE models as well. All that is required is a representation of each consumer's utility function (defined over goods and services) and the consumer's budget constraint or, equivalently each consumer's indirect utility function (defined over prices and income and subsuming optimizing behavior on the part of the consumer).[5] Its use in a PE framework is only sensible if the regulation in question affects only one market without spillovers across markets. Of course, this is precisely the condition required for a PE analysis to be meaningful.

Besides being theoretically motivated and straightforward to measure, individual EVs can be summed to provide an aggregate measure of the social cost of a regulatory policy.[6] In addition to its association with a sensible theoretical framework ("how much would I pay to avoid this policy?"), an EV measure requires an underlying utility function. The appeal is that it makes transparent the goods and non-market services included in the utility function.

Like other metrics provided by the output of CGE modeling, EV or CV measures are only as good as the modeling and data that underlie the results. This is not a drawback of an EV measure itself but a cautionary note that all models require careful construction and parameterization. What is appealing about an EV measure is that the utility function can be examined and the observer can draw his or her own conclusions about the reasonableness of the representation of preferences.

The EV measure has two major drawbacks. First, it cannot be used in bottom up engineering models of regulatory costs. We view this less as a drawback of EV than a drawback of engineering models. What this observation tells us is that engineering models can measure a subset of regulatory costs – the direct compliance costs to the firm. What such models cannot

[4] Not included, however, are the environmental benefits from the regulation. These would be measured as a benefit of the regulation rather than included on the cost side of the ledger.

[5] EV and CV can also be recovered from demand functions (see Hausman, 1981). Introductory economics texts often measure changes in welfare for consumers by the *change in consumer surplus* (ΔCS). This is the change in the area under a demand curve for a particular commodity as its price is changed. ΔCS does not follow directly from any policy-analytic thought experiment, though it does approximate EV or CV when income effects from the price change are small.

[6] This assumes that the social value of a dollar of income is the same across all individuals, an assumption that is implicit in most or all RIA benefit-cost analyses. To the extent that distribution matters, social weights can be applied to individual EV measures to reflect differing values of income to different income groups based on some ethical norm.

measure is consumer responsiveness to those higher production costs including any possible averting behavior by consumers to avoid higher consumer prices (e.g. substitution in consumption).

A second potential drawback of the EV measure is that it is not an intuitive concept for the lay person. People generally understand income, prices, and macro concepts such as GDP. EV is a thought experiment: how much would someone pay to obtain an improvement in air quality. It is a hypothetical that can be calculated given a utility function. But it is not something people regularly think about. The challenge, then, is to explain cost measures using EV to policy makers in a way that grounds the concept in something easily grasped. While not necessarily easy to do, it is important to make the effort.

The two main alternatives to an EV measure are seriously flawed. Using changes in household consumption to measure welfare only captures marketed consumption goods. Omitted from this measure are the value of leisure time and home production, a significant component of household utility. Leisure time can be affected by regulations both in quantity (changes in labor supply directly correlate to changes in leisure) and quality (changes in other elements of utility can affect the marginal utility of leisure). Also omitted from household consumption are any other non-marketed consumption goods. For example, if a regulation or an oil spill restricts activities in one public location (such as a beach), and people have to move their activity to a different and less-suitable public location (a different beach or non-beach public park), then one element of social cost of that policy or the spill is the loss of utility from using the less-suitable location. Those public locations are not marketed goods, and so that cost of the regulation or spill would not be included in any measure of consumption or GDP.

Using changes in GDP to measure welfare is often more flawed than using consumption. Recall that GDP is the sum of consumption, investment, government purchases, and net exports. The first problem with using GDP as a welfare measure is that investment does not affect household welfare today but only in the future as capital formation generates a stream of consumption benefits. Using GDP to measure welfare then creates an attribution problem as well as a double-counting problem. The attribution problem is that changes in GDP today arising from current investment would be counted as a welfare change for today's households, when in fact it should be counted as a welfare change for tomorrow's households. Second, the double-counting problem is that changes in GDP from greater investment today would be counted as a welfare gain today as well as a welfare gain in the future (higher consumption from larger capital stock).

To see a second major flaw with using GDP or consumption as a welfare measure, consider a policy to extract more natural resources today, sell those resources, and use them to produce more goods for consumption. The resulting increase in GDP or consumption would overstate the increase in welfare, because it does not account for the depletion of those natural assets. Similarly, we can view clean air as a natural asset. Any change that uses up some of that clean air (by creating additional air pollution) could increase both GDP and the normal measures of consumption of goods and services, but it would not account for the loss of that natural asset.

Conversely, a policy to clean up the air might reduce normal measures of GDP or consumption even though those measures miss the increased value of those natural assets.

A third major flaw with using GDP as a welfare measure is that it can lead to perverse results. If we use GDP to measure the social costs of regulation, then presumably we would say that regulation is costly if GDP falls (relative to no regulation and abstracting from benefits). To see the fallacy of this approach, consider an investment in environmental abatement capital like a scrubber. That investment contributes to an increase in GDP (assuming it is not entirely offset by a fall in other components of GDP). This increase in turn would appear to support a reduction in the social costs of the regulation when, in fact, just the opposite is true. The scrubber investment is a cost arising from the regulation---not a benefit or cost reduction. It appears to raise welfare in an absolute sense even though its true net impact is zero. Thus, GDP does not distinguish between costs and benefits.

In summary, EV is an appropriate and preferred metric for measuring the social costs of regulation. It is grounded in economic theory, has the potential to incorporate all impacts of regulation on households, and provides a dollar-based measure of social costs that can easily be compared to dollar-based measures of benefits.

3.6. Linking Economy-Wide and Sectoral Models

Charge Question: EPA recognizes that, in some circumstances, the use of multiple models may be advantageous when characterizing the costs of regulation. For instance, an engineering or partial equilibrium model can provide needed sector detail while a CGE model accounts for pre-existing market distortions and how compliance costs in one sector affects other sectors of the economy. In some cases, modelers strive to integrate these two modelling frameworks by establishing hard linkages (i.e. compliance costs are endogenous to the model) or soft linkages (i.e. compliance costs are exogenously specified though the models may be iteratively linked). What conceptual and technical merits and challenges are important to consider when incorporating and potentially linking of detailed sector cost models or bottom-up engineering estimates of abatement costs with a CGE model?

Since federal air regulations are inherently sector- and region-specific in their costs and benefits, some type of linking of bottom-up and top-down models will often be necessary to deliver national scale assessments of such regulations. As noted in US EPA (2015a), there are many different ways to link models for the assessment of air quality regulations. So it is useful to review some of these options, beginning with the simplest and progressing to the more complex and time-consuming. At each stage, we comment on their appropriateness for use at EPA.

Soft linking

This refers to extracting information from sectoral models and inserting it into a CGE model (with the possibility of feedback loops). For example, changes in production cost and the mix of inputs and outputs due to a regulation could be estimated with a detailed industry model and the results used to replace the corresponding baseline solution variables in a CGE model. This form of model linking is only likely to produce useful results if conditions for recursive modeling are satisfied, that is, changes in general equilibrium prices must not have a significant effect on the sector being analyzed. As with other linking methods, soft linking can only be expected to produce sensible results if the sectoral model uses data consistent with that in the CGE model and shares a structure consistent with profit maximization. Serious structural inconsistencies will make translation of sectoral results into variables in the general equilibrium model arbitrary, and make it impossible to use feedback loops to take changes in sectoral input and output prices into account. These problems exist with all linking methods, but the soft linking method has no built in checks of convergence or consistency to make them apparent. To make the results replicable, the linking procedures as well as the sectoral model must be documented adequately, and consistency of the sectoral and general equilibrium models addressed explicitly. Use of proprietary sectoral models in particular will limit replication to researchers with access to the sectoral model. Soft linking is not necessarily an invalid approach, but each instance must be evaluated critically if it is used in regulatory analysis.

There are separate issues associated with soft links between the natural systems that receive emissions and the resulting changes in environmental quality. As noted earlier there has been limited attention given to evaluating these soft links. Smith and Zhao [2016] showed in a small simple model that such soft links were equivalent to assuming separability of all non-market goods.

Summary function approach

This is the next most common way of linking models. It involves summarizing key economic information from a bottom-up model (usually an engineering-economic approach) in the form of an aggregated functional relationship and imbedding that in the CGE model. This summary function can represent a marginal abatement cost (MAC) curve, or it could be a more sophisticated minimum cost, maximum revenue, or profit function. In the latter cases, the function can include a policy variable representing the stringency of the regulation and, as the regulation tightens, causes costs to rise, or revenues or profits to fall for the affected sector. For example, Pelikan, Britz, and Hertel (2015) use a restricted revenue function to represent the aggregate behavior of a bottom-up model of EU agriculture, wherein the policy variable represents the stringency of the EU regulation for setting aside land for biodiversity. Rose and Oladosu (2002) insert a MAC representing forest sequestration of carbon into their CGE model of the U.S. economy to complement their analysis of the macroeconomic costs of mitigation in a cap and trade system for greenhouse gases. In the case of a MAC curve that is embedded in a CGE model, resource requirements in the sector rise with increasing levels of abatement. The MIT Emissions Prediction and Policy Analysis (EPPA) model has used this approach widely to represent non-CO_2 GHG abatement possibilities. The benefits of incorporating MACs into a CGE model are mainly due to the addition of mitigation opportunities and technology detail not already present in the model. Care does need to be exercised in the application of MACs and interpretation of results due to some of the limitation of this approach, including: (a) the static nature of MACs in that the engineering-economic estimates are usually done for an implementation initial year, e.g., 2020 and assume a technology lifetime and fixed prices; (b) difficulty in estimating technology developments over time; (c) negative-cost abatement—generally related to a fixed market price for energy or commodities (such as cost savings from energy-efficiency improvements)—that are inconsistent with the typical cost minimization behavior usually imposed in CGE models (i.e., CGE models would typically assume that all cost savings from energy efficiency improvements have already been achieved).

The summary function approach is attractive for repeated analysis, provided the relevant policy variables are very clear—either in the CGE model, or in the summary function itself. However, when the air regulation is more complex, this approach may not be sufficient.

Sequential calibration

This is a more sophisticated means of linking two models, invented by Tom Rutherford, and applied to many different problems (Bohringer and Rutherford, 2008). It was originally intended to facilitate linking of a bottom-up electricity model with a top-down CGE model. Its implementation is relatively straightforward. A constant elasticity supply function (e.g., for electricity) is introduced into the CGE model. The two models are then run in sequence, successively recalibrating the supply function until the equilibrium price and quantity of electricity is in agreement between the two models. Experience suggests that this tends to converge rather quickly, thereby ensuring that, for the common variables, the two models are in agreement. However, if the power-sector regulation encourages capital-intensive renewable energy technologies, for example, this increased demand for capital should be carried over in the integration with the CGE model. Otherwise, sequential calibration would fall short of providing the full set of general equilibrium impacts of the regulation. Another complication is that typically the engineering model will incorporate more granular concepts of prices for inputs or the goods being produced, so that some formula will be required to transform multiple prices in the engineering model into a single price in the CGE model and vice versa.

Disaggregation of the CGE model

In order to establish full consistency between a technology-rich bottom-up model and a CGE model, it is necessary to actually integrate the bottom-up technologies into the CGE model. This has been done in the case of the electric power sector [e.g., Sue Wing (2006); Sue Wing (2008); Peters (2015)] and for the transportation sector (Kiuila and Rutherford, 2013). It can be extended to the entire energy sector and its main consumers by using a detailed activity analysis model, such as MARKAL. With the individual power generation technologies (and transmission and distribution activities in the case of Peters' work) broken out in the CGE model, one is now assured of capturing the factor market impacts of air regulations. This kind of disaggregation is time-consuming and difficult, as it involves bridging engineering and economic data and concepts. It is most likely to be worthwhile for sectors that have many linkages with the rest of the economy, as is the case with the electric sector, and when EPA anticipates carrying out multiple analyses of regulations affecting the sector in the future.

3.7. Economy-Wide Approaches Other than CGE Modeling

Charge Question: When EPA has estimated the economic effects of regulations on multiple markets it has relied primarily on CGE models, such as the EPA-developed EMPAX and the Jorgenson-developed IGEM models. Are there other economy-wide modeling approaches beside CGE that EPA should consider for estimating the social costs of air regulations (e.g., input-output models, econometric macro models, dynamic stochastic general equilibrium models)? What are the potential strengths and weaknesses of these alternative approaches in the environmental regulatory context compared to using a CGE approach?

Dynamic stochastic general-equilibrium (DSGE) models are conceptually similar to CGE models, in that they are computational general-equilibrium economy-wide models built upon microeconomic foundations. The most obvious difference between DSGE and CGE models is that DSGE models are stochastic whereas very few CGE models explicitly incorporate uncertainty in productivity levels or other exogenous variables. In addition, because DSGE models are used primarily to model aggregate macroeconomic issues, such as economic fluctuations, growth, and the effects of monetary and fiscal policy, they typically model only one industry, whereas CGE models typically have much more industry disaggregation.

Industry disaggregation is vital for modeling environmental policies, because such policies often target only a relatively narrow sector of the economy (and even for policies that apply more broadly, some sectors of the economy are affected far more than others). Thus standard DSGE models are not likely to be useful for EPA's purposes. Nonetheless, there is potential for developing hybrid models – either by starting from a standard DSGE model and disaggregating industries or by starting from a dynamic environmental CGE model and integrating uncertainty – that could be very useful for looking at issues that are hard to address with current models, such as interactions between environmental regulations and business cycles. However, such hybrid models would be highly complex, and thus subject to the various concerns that come with complexity (such as potential lack of transparency).

Other modeling approaches are often used for economy-wide modeling, but are not recommended, in their current form, for use by EPA to analyze social costs. Input-output (I-O) analysis is a model of all purchases and sales between sectors of an economy, based on the technical relationships of production (Miller and Blair, 2009). Although it is still widely used for policy analysis, it is far from the state-of-the-art. Its major strengths (e. g., multi-sector detail, full accounting of all inputs, and focus on interdependencies) are all captured by CGE modeling, which also overcomes I-O limitations of lack of behavioral content, absence of the workings of prices and markets, and lack of explicit constraints on resource availabilities (Rose, 1995). Conjoined I-O/macroeconometric models typically just add a forecasting driver to an I-O model rather than being a fully integrated version of the two models (Rey, 1998). A major exception is the Regional Economic Models, Inc. (REMI, 2015) Model, which is fully integrated, and with many of its components based on time series estimation. It also includes some aspects of general equilibrium modeling in its labor market module and can readily be used in cases where regulations are such that they require non-price responses.

These other modeling approaches can calculate economic impacts, broadly defined, but most of them cannot yield standard welfare measures used in benefit-cost analyses because they lack formal utility or demand functions. A more extensive assessment of these modeling approaches appears in Section 5.6. In addition, macroeconometric models (and other models that include a reduced-form macroeconometric component, such as the REMI model and other conjoined I-O/macroeconometric models) are typically subject to the well-known Lucas Critique (Lucas, 1976). Such models are based on historical correlation patterns in macroeconomic data, and policy changes are likely to change those patterns. Thus, while such macroeconometric models can be very useful for short-term forecasting, using them to analyze the effects of policy changes, particularly over the long run, can be misleading. In particular, it can lead to results that are the opposite of unambiguous qualitative results that can be derived from analytical models.

As noted in Sections 3.1 and 3.6, in some circumstances it may be best to use a suite of tools including engineering, PE and CGE models. The appeal of a CGE model lies, in part, in its comprehensiveness: by including interactions throughout the economy it can potentially capture costs and benefits far upstream or downstream of the point of regulation. However, that comprehensiveness also presents challenges. Limitations in data or the existing literature may make it difficult to specify parts of a CGE model that would be critical for analysis of certain air regulations in a way that is both transparent and robust. In those circumstances, EPA would be better served by a linked analytical approach than by attempting to use a CGE model alone.

Finally, in some cases, EPA may be best served by using multiple CGE models in parallel. This approach would be most useful when there is little evidence or consensus on a key analytical issue that determines how the economy will respond to a proposed regulation. It has been used fruitfully in the analysis of tax policy by the Congressional Budget Office (CBO) and Joint Committee on Taxation (JCT). In response to a mandate in the 2016 budget resolution that required a move from static to dynamic scoring, CBO and JCT have used a behavioral Solow growth model and an optimizing overlapping generations model in parallel to find key channels that are ignored by static scoring. They then explored the net revenue consequences of allowing for those channels, drawing on a broad literature to estimate the response of the economy to the proposed policy. For example, the CBO has used dynamic scoring to examine the impact of a repeal of the Affordable Care Act, finding that "macroeconomic feedback" through the labor market would significantly moderate the revenue reduction from repealing the act. Edelberg (2015) is a presentation describing CBO's current approach to dynamic scoring.[7]

4. MEASUREMENT OF BENEFITS

4.1. Conceptual and Technical Hurdles in Economy-Wide Modeling

Charge Question: Setting aside costs for the moment, what are the main conceptual and technical hurdles to representing the benefits of an air regulation in a general equilibrium framework (e.g. data requirements, developing detailed subsections of the model such as more realistic labor markets, scale and scope)? What would be required to overcome them?

The technical and conceptual hurdles to representing benefits from air pollution policy center on the tension between CGE models, which tend to be highly aggregated (spatially), and impacts from air pollution exposures which tend to vary across space.

Although the level of regional disaggregation varies across CGE models, they are all still fairly aggregated. This may present a problem when modeling pollutants with specific localized effects in a national analysis. We note that economically important air pollutants such as fine particulate matter have highly localized as well as regional effects. The central question becomes: what is missed when linking spatially heterogeneous air pollution information to a spatially-aggregated CGE model? Secondly, would the use of a spatially-aggregated CGE model result in a biased estimate of the benefits of an air pollution regulation?

The question of *how* a CGE model is aggregated may determine whether there are adverse consequences of representing spatially heterogeneous air pollution benefits in a national CGE model. For example, aggregating according to airsheds rather than administrative boundaries would help align the model with exposure to pollutants, although it would still not capture intra-airshed variability and would complicate modeling of policies imposed at the state, rather than airshed, level. However, realigning a CGE model according to airsheds may not be necessary if the economic feedbacks from the benefits of air pollution control are weak. In that case, benefits modeling could be conducted separately from CGE modeling of costs. This approach would provide high spatial detail on benefits modeling, which is necessary in the context of local air pollutants, without requiring matching disaggregation of the CGE model. And, concurrent CGE modeling could proceed in an aggregated fashion without concerns about missing benefit-side feedbacks.

[7] It should be noted that CBO and JCT use this approach only for proposed legislation that is likely to have major impacts far larger than the vast majority of air regulations. We mention it to illustrate the value of parallel models but do not recommend it for routine use at EPA. Rather, it is a long term strategy that may be useful for improving economy-wide modeling over time.

Conversely, if general equilibrium benefits of air regulations are expected, the next question is whether the feedbacks themselves will vary spatially. If such general equilibrium effects are not expected to vary across space, then the aggregated approach may be adequate. If the feedbacks are liable to exhibit heterogeneity, then the modeler faces a decision as to whether geographically disaggregated approaches are justified for all sectors, or if disaggregation could be targeted at particularly relevant sectors. Also note that even in cases when spatial heterogeneity would make it difficult to accurately measure general-equilibrium effects on the benefit side, other approaches would miss those effects entirely, so even a highly imperfect general-equilibrium analysis could still be valuable.

In view of the current empirical evidence suggesting that benefits of air pollution regulations are primarily due to reductions in premature mortality risks, it is important to consider how reduced mortality benefits will have general equilibrium effects. As such, a channel through which such benefits may have general equilibrium effects is through the time endowment. However, if this is the primary linkage between air pollution policy and benefit feedbacks and the labor supply is relatively mobile, then the advantage to a spatially disaggregated CGE model is likely to be low and an aggregated model will not be biased.

A final consideration focuses on dynamic modeling. In a spatially-disaggregated CGE approach, the principal advantage of spatial detail is the ability to allocate production, and therefore emissions, to particular regions. Parameterization of such models is challenging because detailed time-series data are often unavailable for finely-detailed geographic regions. As a result, parameters are often based on extant regional patterns in economic activity. A problem then arises when conducting spatially-resolved CGE in a dynamic setting. In particular, the modeler would need to make difficult decisions regarding the location of new facilities and the location of retired facilities in the absence of historical data. These prospective choices would be very difficult to make with any degree of precision and this component adds to the difficulties associated with using spatially-disaggregated CGE models.

Additional obstacles or challenges associated with representing benefits of air regulations in a general equilibrium framework include: modeling regulated firms' actual responses in the face of myriad policy constraints (see Section 3.4), the disparity in valuation techniques applied in non- and CGE contexts (see Section 4.2), and recognition of possible biases in underlying risk estimates associated with exposure to air pollution.

Regulated firms' response to policy depends on many factors. These include instrument design, abatement technology choice, the degree of compliance, and firms' objectives. While most of these challenges are not necessarily unique to CGE models, the crucial dimension of CGE that relates to these obstacles is the degree of aggregation implicit in most CGE models. That is, highly aggregated models may miss or omit within-sector variation in these factors, which may have important implications for both costs and benefits.

As stated above, a significant share of air pollution control benefits emanate from reductions in mortality risk. These risk estimates, in turn, depend on concentration-response functions estimated by epidemiologists (Krewski, et al., 2009; Lepeule, Dockery, & Schwartz, 2012). Again, while resolving any underlying methodological issues is not within the purview of CGE modelers or this panel, the strong dependence of benefits on these risk estimates suggests the need for parsimonious CGE models that facilitate or enable rich sensitivity analyses and are not incorrectly perceived as improving validity by adding complexity.

Many prior analyses that estimate the monetary benefits of air pollution policy employ valuation techniques based on willingness to pay (WTP) measures, such as the Value of a Statistical Life (VSL). These methods tend to produce benefits estimates that are large relative to abatement costs (USEPA, 1999). In addition, these benefit estimates comprise a significant share of national output. In particular, the benefits of the Clean Air Act have been estimated to be between 15% and 20% of wage income. Smith and Zhang (2016) derived these estimates by comparing them to the aggregate wage bill. In stark contrast, CGE-based assessments that model benefits of air pollution regulations through impacts on the population's time endowment generate much smaller monetary benefit estimates. (A more thorough discussion of these differences is found in Section 4.2.) With effects this large, at least those generated using WTP measures, an important consideration is the degree of separability between non-market (associated in part with changes in mortality risks) benefits and other goods consumed by households. Thus a remaining conceptual and empirical challenge is the specification of utility functions that can suitably capture both non-market and market goods and the estimation of parameters within the utility function.

4.2. Equivalent Variation and Willingness to Pay for Risk Reductions

Charge Question: Benefits estimates for air regulations are often predicated on individuals' willingness to pay for risk reductions, while economy-wide models yield information on changes in overall welfare (e.g. changes in equivalent variation or household consumption), usually limited to market-based impacts. How do we reconcile these two measures? What type of information does each of these measures convey?

Environmental benefits have not typically been included in equivalent variation (EV) measures derived from CGE modeling. When benefits have been included, analysts most commonly focus on market-based or human-capital measures. Principal among these are adjustments to the labor or time endowments allocated to agents in the model based on the mortality risk reductions generated by the regulation. From the projected improvement in environmental quality and the dose-response functions that underlie partial equilibrium benefits estimates, one can predict the additional worker-hours that would be supplied to the economy. Adding these workers to the labor or time endowment implies that their effects on income and prices then form part of the basis of the counterfactual policy analysis.

In contrast, most of the benefits of environmental improvements typically estimated and included in EPA's benefit-cost analyses are calculated from PE measures of individual willingness to pay for risk reductions. These willingness to pay estimates are often based on wage-hedonic models that attempt to isolate the effect of differences in on-the-job risk across employment types on market wages (US EPA, 2010f). If workers are optimizing over the characteristics of jobs, then these wage differentials capture the maximum reduction in earnings that workers would accept to occupy a marginally less risky occupation. Thus, one is left with estimates of marginal willingness to pay for risk reductions (or a value of a statistical life, VSL). These numbers are then multiplied by estimates of the size of the environmental risk reduction expected from the policy change and scaled up to the size of affected populations to produce estimates of the aggregate benefits of the policy.

Both methods aim to capture the effect of changes in mortality generated by the policy. Beyond this similarity, however, the two measures may diverge for a number of reasons and reconciling them is important. Beyond characterizing the type of benefits (mostly premature mortality risk reductions), whether there are general equilibrium effects (if so, primarily through the time endowment) and whether or not these vary across space (not if labor supply is mobile or beneficiaries are retired), an important issue is that the magnitude of effects derived from willingness to pay measures are such that there likely are important general equilibrium impacts. For example, the benefits of the Clean Air Act have been estimated to be between 15% and 20% of wage income. Smith and Zhao (2016) derived these estimates by comparing the benefits to the aggregate wage bill. With effects this large, an important consideration is the degree of separability between those benefits and other goods consumed by households. In particular, how do these gains translate into behavioral impacts? Although the impact of most other environmental regulations will be smaller in terms of aggregate willingness to pay, the key point here is that willingness to pay measures of benefits are often substantial, and when they are it is likely that there are corresponding general equilibrium consequences. Moreover, there will be general equilibrium effects from allowing environmental services to enter preferences in a non-separable way. In the discussion that follows, we primarily focus on mortality risk reductions because it is the single-most important category of benefits in benefit-cost analyses of major air quality regulations.

Murphy and Topel (2006) provide a useful conceptual framework for analyzing willingness to pay for improvements in health and longevity. We briefly describe it here as an aid to understanding the key differences between CGE and VSL measures of mortality impacts. The authors model a household lifecycle consumption problem that accounts for the effects of life-extension and amenity-based measures of health. The household chooses levels of consumption, savings and labor supply to maximize expected utility over an uncertain life length.

A comparative static exercise yields an expression for willingness to pay for an incremental reduction in the risk of death, the marginal willingness to pay for a reduction in mortality risk (or VSL) for an individual currently of age *a*:

$$MWTP(a) = \int_a^\infty \left[y^F(t) + c^F(t)\phi\big(z(t)\big)\right]e^{-r(t-a)}S(t,a)dt$$

where $y^F(t)$ is full income at age t (defined as money income plus the value of leisure time); $c^F(t)$ is expenditures on full consumption at age t (defined as market-based consumption plus the value of leisure time); $\phi\big(z(t)\big)$ is consumer surplus per dollar of full consumption at age t; $S(t,a)$ is the probability of survival to age t conditional on having survived to age a; and $e^{-r(t-a)}$ is a standard discount factor.

The expression contains a couple of important insights. First, it makes clear that VSL should capture the value of non-market assets and consumption.[8] For example, extending the lives of retirees generates no additional earnings but clearly has economic value. CGE applications that fail to account for non-market activities (including the value of leisure time) are likely to underestimate the value of life extension for this reason.

Second, existing CGE applications that do account for non-market time could, in principle, generate impacts that are consistent with the VSL expression above. That is, a change in the size of the time endowment would be expected to generate changes in full income and consumer surplus.

Beyond this broad correspondence, however, differences in the treatment of any of the terms in the VSL expression represent opportunities for CGE and VSL-based calculations to diverge. In particular, the surplus generated by consumption in CGE models will depend on the parameterization of the agent's utility function. Without a strategy for linking the information contained in VSL estimates to the preferences described by this utility function in a theory-consistent manner, we have no reason to expect CGE and VSL-based measures of mortality impacts to have any relationship to each other.[9]

Perhaps an even more basic reason these measures may differ is because the standard VSL-based calculations are not embedded in a complete demand system. Conceptually, VSL captures willingness to pay for a small change in risk; that is, for changes involving relatively small amounts of virtual expenditure relative to income. Using it to evaluate the benefits of risk reductions involving large changes in virtual expenditure could overstate the benefits by failing to acknowledge the limits imposed by budget constraints and the effects of diminishing marginal

[8] Murphy and Topel (2006) focus on the value of leisure time but the logic applies just as well to the value of other non-market goods and services including environmental amenities.

[9] What shape such a strategy should take remains an open question. Murphy and Topel (2006) specify an intertemporal utility function which includes the value of leisure and describe a strategy for calibrating it using empirical estimates of VSL and key preference parameters. Smith et al (2003) describes an approach combining structural assumptions regarding preferences with empirical estimates of the labor supply elasticity, baseline job risk and wages to imply a value for VSL. Alternatively, Chetty (2006) establishes a theory-consistent link between the labor supply elasticity and the coefficient of relative risk aversion that could be used to calibrate preferences using VSL estimates.

utility – both features that are present when modelers use a utility-maximization approach to measure welfare impacts. As a general guide, when a VSL-based calculation of risk implies benefits that represent a significant fraction of household income or when the nature of the risk is likely to involve strong non-separability between environmental outcomes and other behaviors, modeling the benefits as part of a complete demand system may be an important step in understanding the true impact of a regulation.

These reasons are likely to explain much of the difference between the quite modest estimates of environmental benefits that have been produced by CGE-based studies of the Clean Air Act Amendments and much larger estimates based on VSL calculations. A new strategy for specifying and estimating the preference functions described in CGE models that is capable of incorporating VSL information in a theory-consistent manner would be required to produce comparable benefits estimates from using the two methods.

We now explore what the benefit might be from developing these types of comparisons using general and partial equilibrium approaches. At least two issues seem relevant here. First, CGE models could provide a vehicle for modeling benefits within a complete demand system, ensuring that all sources of policy costs and benefits are accounted for and all resource constraints acknowledged. Beyond the specific issue of constraining VSL calculations by available budgets, having a complete accounting framework that avoids, for example, double-counting of benefits where overlap between categories exists and demonstrates how different categories of benefits are related has value.

Second, partial equilibrium approaches assume either that all other prices in the economy remain constant with the introduction of the policy or that they have no bearing on (are separable from) demand for environmental quality. This assumption may not hold for any number of reasons. For example, many CGE analyses predict important impacts of environmental regulation on factor prices. The VSL formula above makes clear that accounting for these changes is important: the value of mortality risk reductions would be expected to depend on the future factor earnings of impacted households.

Moreover, many of the techniques used by economists to value environmental quality are predicated on the belief that the environment is either a complement or substitute for some market-based activity. Observing how the demands for these related goods vary with environmental quality allows us to infer its value. At the very least, this points to a logical inconsistency between the models used to estimate the value of environmental quality and the way these estimates are employed in benefit-cost analyses. Whether it represents more than a logical inconsistency is an empirical matter that remains to be explored. However, one can easily construct scenarios in which these types of relationships might be important; a new regulation affects both the price of transport fuels and the environmental quality of recreation sites, so the benefits of the quality improvements are overstated to the extent that they fail to account for the increased costs of travelling to visit them.

We might also expect non-separabilities to be the source of changes in demand for market goods, which could be important in evaluating the costs of policy to the extent that these markets are distorted (see Section 3.1).

In summary, we see a few different roles that CGE models might play in modeling environmental benefits. The first is to provide a consistent accounting framework: the simple act of writing down a complete set of expenditure and income categories imposes a useful discipline on the analyst. Ensuring that, for example, willingness to pay for the improvements in environmental quality imagined by policymakers is, in fact, constrained by available income is an important reality check. The second role CGE models might play is to explore how important price changes in related markets are likely to be as a determinant of a policy's anticipated benefits. Finally, the models may also be useful in describing how changes in environmental quality affect the responses of other parts of the economy to policy changes through non-separable relationships.

Our discussion has stressed the importance of modeling non-market activities and parameterizing CGE models using empirical estimates of willingness to pay for environmental quality if one is to reconcile partial and general equilibrium estimates of benefits. Here we briefly discuss strategies for operationalizing these ideas.

One might argue that – because CGE analyses of environmental regulations have historically focused on impacts that occur within the market economy – it is natural to focus on market-based impacts as an avenue for including benefits in these models. Yet the conceptual step required to include non-market environmental impacts in these models is a small one. In fact, as we next explain, a close parallel exists in the approach researchers currently use to include leisure activities in CGE models.

CGE models that do not account for leisure specify labor endowments for households as the wage earnings reported in the input-output tables used in the model parameterization. To account for the value of leisure activities, modelers expand the definition of the household's endowment to cover time as a resource that may be divided between market (labor supply) and non-market activities (leisure demand). The value of the time endowment is based on the benchmark wage rate – the shadow price of the agent's time in the benchmark equilibrium of the model if she is optimizing her mix of labor and leisure activities. The agent then assesses her full income, including both market and non-market components, in choosing consumption activities (including the demand for leisure). While no physical outlay of money is associated with the leisure transactions, the model accounts for the economic value of these activities using standard tools from consumer theory.

The same logic applies to the task of including non-market values from improvements in environmental quality into a CGE model. Households are endowed with a level of services derived from environmental quality in the benchmark equilibrium to which the model economy is calibrated. The shadow price used to place a value on this endowment is an empirical estimate of the aggregate marginal willingness to pay for improvements in environmental quality. The agent then assesses her full income, including conventional market-based components as well as the value of the environmental endowment, in choosing consumption activities. How environmental services enter the agent's utility function controls the degree to which the environment functions as a substitute or complement for the other consumption activities described in the model. In policy experiments, the environmental impacts of new regulations are reflected in changes in the size of these endowments.[10]

Two key pieces of information would be required to credibly parameterize such a model: an estimate of aggregate marginal willingness to pay for environmental quality (such as a VSL estimate) and information on the substitution patterns between quality and the other arguments that enter the utility function. On the first count, no information beyond what is currently used in current PE benefits calculations is required. Information on aggregate substitution patterns is not currently available. Nevertheless, researchers could explore the sensitivity of benefits estimates to a range of elasticity assumptions.[11]

Finally, it is worth reflecting on how CGE models are likely to best serve EPA's mission to inform stakeholders about the benefits and costs of environmental regulations. CGE models are unlikely to be successful at producing precise estimates of policy benefits. For example, interactions between environmental quality and other elements of the demand system are matters for which we have scant empirical evidence. Sensitivity analysis is essential.

Perhaps the most important point to be made here is that expecting CGE models to provide more precise estimates of benefits than other approaches is to misunderstand what this set of tools has to offer. In fact, due to the large number of parameters needed in a CGE model, as well as to the high degree of aggregation that may be required, a CGE analysis is likely to produce less precise results than a PE or engineering study. However, the real strength of the approach is that it reduces potential bias by capturing important interactions that would otherwise be omitted. That is, CGE results will be less precise but able to present a more complete picture of the operative policy responses. Moreover, a CGE model provides a tool through which researchers can reduce

[10] See Carbone and Smith (2008) and Carbone and Smith (2013) for formal descriptions of modeling strategies based on this logic. Including environmental quality arguments in the utility function – as this approach calls for – is a natural way to model amenity-based environmental services, where the environment is being combined with time and market goods to produce well-being. However, it might also serve as a useful shorthand for including VSL information into single-period CGE models, where explicitly modeling a stream of future benefits from life extension is not possible. Dynamic models could, in principle, follow a strategy derived from the logic of Murphy and Topel (2006). These are issues that remain to be explored.

[11] It is worth pointing out that the lack of empirical estimates of substitution elasticities is not unique to modeling environmental benefits. For example, much of the literature evaluating the efficiency costs of environmental regulation in an initially distorted economy (which relies heavily on the use of CGE models) assumes that leisure demand is weakly separable from other consumption for lack of good empirical estimates of the relevant substitution elasticities. A lack of an empirical foundation for this assumption has not stopped researchers from using these models for policy analysis.

the tradeoff between precision and completeness by testing which interactions matter and which are unimportant. If general equilibrium interactions are shown to matter little for determining benefits of a particular air quality regulation, non-CGE approaches introduce little bias and are sufficient. If some interactions do appear important, a CGE approach is warranted: a PE approach would be incomplete. To determine which such interactions are important, an approach analogous to that discussed in Section 3.1—for determining when general equilibrium effects are most important for assessing costs—could be used.

4.3. Public Health and Economic Activity

Charge Question: What are the conceptual and technical challenges to constructing the relationship between public health and economic activity? How can we best capture and communicate the uncertainty surrounding this relationship?

The links between air regulations, public health and economic activity are complex and discussed in detail in responses to other charge questions. As noted in Sections 4.1 and 4.11, spatial heterogeneity may be important, both in concentrations of pollutants and in the demographic characteristics of populations exposed. As discussed in Section 4.2, air quality will have impacts on morbidity and mortality that affect the economy through changes in the effective labor supply. Section 4.5 provides further discussion of morbidity and mortality impacts and then goes further to discuss the impacts of air quality on: (1) the demand for health care, (2) the consequences of that care for health status, and (3) residential sorting among households with different willingness to pay for reduced health risks. Section 4.6 discusses the feasibility of linking health to changes in employment status that may result from regulatory changes. Section 4.7 provides discusses the link between health status and the demand for goods other than health care, as well as providing further discussion of the link between air quality and the demand for health care itself. Finally, Section 4.8 discusses the link between air quality and productivity.

4.4. Modeling Impacts as Changes in Household Time Endowments

Charge Question: For the Section 812 study, EPA modeled mortality and morbidity impacts (e.g., benefits from reduced premature mortality due to reduced PM2.5 exposure) in a CGE framework as a change in the household time endowment. Is it technically feasible and appropriate, and does the empirical literature credibly support, the modeling of mortality and morbidity impacts as a change in the time endowment? If not, what key pieces of information are needed to be able to incorporate mortality and morbidity impacts into a CGE model? Are there other approaches to incorporating these impacts that warrant consideration?

Modeling a change in the time endowment is technically feasible and numerous studies support the appropriateness of modeling mortality and morbidity as a change in time endowment (Burtraw et al., 2003; Yang et al., 2004; Matus et al., 2008; Nam et al., 2010, Matus et al., 2012;

Saari et al., 2015), but other channels for capturing the impacts of reduced $PM_{2.5}$ exposure (like labor force participation, change in health care services and expenditures) should be considered as well. Mortality and morbidity impacts can be modeled as changes in market effects (lost wages, and expenditures on health care) plus some valuation of the non-market effects of illness—pain and suffering and associated loss of enjoyment or attention to household activities because of the illness. In a CGE framework, the components of these valuation estimates can be included. Specifically, hospital costs can be treated as a demand for medical services, lost work time can be treated as a reduction in the labor force (in dollar equivalents), and damages beyond these market effects can be treated as a loss of leisure. Yang et al. (2004) use this approach and provide a methodology for integrating health effects from exposure to air pollution into a CGE model. Matus et al. (2008) apply this method to examine the economic consequences of air pollution on human health for the U.S. for the period from 1970 to 2000. The Matus et al., (2008) study addressed benefits from reductions in tropospheric ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, and particulate matter. Other examples of the studies incorporating cost of illness, lost work time and loss of leisure are Nam et al. (2010), where welfare losses caused by air pollution in Europe are estimated, and Matus et al. (2012), where health damages from air pollution in China are assessed. These analyses include economic and welfare effects of pollution-related health outcomes by explicitly accounting for morbidities and mortalities and explicitly representing a household production sector for "pollution health services", but they do not consider feedback effects of pollution on the associated levels of the nonmarket services (see discussion in Sections 4.5 and 4.9).

To incorporate mortality and morbidity impacts into a CGE model, detailed emissions-impact relationships, including information from source-receptor atmospheric modeling and updated information on concentration-response functions and associated costs are needed. Examples of studies that provide information on concentration-response functions are Holland, Berry, and Forster (1998) and Pope, et al. (2002). Based on the detailed emissions-impacts relationships, Burtraw, et al. (2003) provide an examination of health effects from changes in NOx emissions in the electricity sector and calculate ancillary benefits from modest carbon taxes. An air quality modeling system is linked to a U.S. computable general equilibrium economic model in a study by Saari et al. (2015) where they also use emission-impact relationships to represent the economy-wide welfare impacts of fine particulate matter. Whether the studies use a CGE or PE approach, they require validated epidemiological relationships between air pollution concentrations and the resulting health impacts, and the valuation of so called "endpoints" (such as respiratory hospital admissions, cardiovascular hospital admissions, myocardial infarctions, etc.) that represent medical costs and lost wages. The factors that affect the choice for using a CGE versus a PE approach are discussed in Section 3.1.

Another approach for incorporating the economic impacts of air pollution includes estimates of willingness to pay (WTP) for reduced health risks (Bell, Morgenstern and Harrington, 2011). WTP estimates for reduced mortality risk are discussed in Sections 4.2 and 4.5. The major condition for a consistency between WTP and CGE welfare measures includes the constraint on

WTP imposed by the household's budget. Smith and Carbone (2007) discuss the theoretically preferred approach to incorporating air quality preferences in CGE models. The benefits and challenges of their approach are discussed in Section 4.5.

4.5. Other Representations of Mortality and Morbidity

Charge Question: Approximately 95 percent of monetized benefits of air regulations arise from willingness to pay for reductions in the risk of premature mortality, which is not equivalent to the value of the change in the household time endowment…

4.5.1. Empirical research to support other representations of direct impacts

Charge Question: Is there sufficient empirical research to credibly support incorporating other representations of mortality and morbidity impacts or additional benefit or dis-benefit categories?

Benefit analyses for conventional air pollutants, as documented in US EPA (2015b), have been organized around an established logic that relies on a damage function approach. The largest share of these health related benefits is associated with mortality effects. Risk changes due to reductions in the ambient concentrations of one or more air pollutants are monetized using estimates for the value of a reduction in mortality risk (VSL). The first component of the charge question asks if there is "sufficient empirical research to credibly support … other representations . . ." of the damages. The focus of this question is implicitly on whether other methods capture health effects associated with morbidity and mortality as well as the other sources of damages.

To address the first component of this multi-part question, there is, in our opinion, a sufficient empirical support for hedonic property value models' estimates of the effect of air pollution on housing values. An early meta-analysis by Smith and Huang (1995), more recently hedonic modeling by Chay and Greenstone (2005), and the hedonic property and wage modeling by Bieri et al. (2014) as well as numerous other studies confirm that air pollution measures are statistically significant influences on residential property values. With that said, there are several difficulties applying this literature at the national level, as we note in response to the following questions:

- Do they offer sufficient resolution for specific pollutants that would match the detail of the damage function research? Answer: no, not at this time.
- Do they offer sufficient coverage of different urban areas to be used on a national scale in lieu of that damage function approach? Answer: no, not at this time.
- Can these health effects be isolated from other motivations for avoiding air pollution? Answer: no, not at this time.
- Have these studies been tested for spatial confounding effects of unobservables? There is at least one study with these types of tests in the hedonic context. It relates to early

experience (Chay and Greenstone, 2005). Based on Kuminoff and Pope (2014), when evaluating hedonic models in a different application one would raise issues about how these types of estimates should be interpreted.

However, these responses do not preclude the use of hedonic property value estimates as part of a plausibility analysis (discussed in detail in Section 6.1) of benefit assessments based on the conventional strategy using VSL estimates. For national scale policy analyses involving important rules, the use of estimates from multiple methods as part of a plausibility analysis could be conducted as part of using a CGE model. The earliest research attempting to develop benefits measures for improvements in air or water quality by Freeman (1982) used this logic to develop plausible or best available estimates.

Equally important, one might consider the strategies used in other contexts to connect estimates for the VSL to estimates for the labor supply elasticity. Smith et al. (2003) exploited this connection in their discussion of preference calibration. However the link is not limited to this case – Chetty's (2006) link between risk preferences and labor supply measures, Hall and Jones' (2007) analysis of the value of life and health spending, Weitzman (1998) and Gollier and Weitzman (2010) on selecting discount rates in the face of risky decisions are all examples of these types of linkages.

The use of preference calibration strategies would yield a wider range of estimates for VSL. More generally, this logic (see Smith et al., 2002) addresses issues that are similar to what must be considered in introducing non-market services into CGE models. As noted in Section 4.2, these issues arise from considering how the tradeoff measures recovered in different contexts—labor markets with hedonic wage models, labor markets with labor supply models, or hedonic property value models--relate to a single economic model of individual preferences.

Incorporating mortality and morbidity into a CGE model in a manner that allows computation of an equivalent variation for changes in morbidity and mortality requires introducing these effects into the specification of an individual utility or expenditure function. More specifically it requires that the preference function be specified to take account of how mortality and morbidity contribute to individual well-being. Smith and Carbone (2007) illustrate how this can be done with a comparison of the use of willingness to pay measures derived from VSL and hedonic property value models in an amended version of the Goulder-Williams (2003) model. To account fully for the general equilibrium effects of regulation of pollutants that affect mortality and morbidity, it is also necessary to represent the generation of pollutants from consumption or production activities and map pollutants into health outcomes. To address the cost of morbidity fully, it is also necessary to incorporate the production and consumption of health care and how health care expenditures change the effects of pollution on morbidity and mortality.

Given adequate data or appropriate parameters from the literature, it is a straightforward programming exercise to extend a CGE model to include these features. Examples of models that deal generally with the representation of material flows and externalities do exist in the literature (Ayres and Kneese, (1969), Noll and Trijonis, Espinosa (1996), Espinosa and Smith (1995), Carbone and Smith (2008, 2013)). To our knowledge there are no off-the-shelf models that could be used by EPA without further development for benefit-cost analysis of health effects associated with air regulation other than the EMPAX-CGE model used in the EPA "prospective" study of Clean Air Act regulations (US EPA 2011, Chapter 8), which incorporates some but not all of the features described above. Although modifying an existing model written in a flexible programming language would take a matter of weeks, obtaining data to estimate or calibrate the relevant valuations and elasticities, and choosing nesting structures and functional forms for equations in the CGE model to represent substitution and complementarity relationships (for nonseparable goods) or control technologies would require a substantial research effort.

The sequence of models below represent how morbidity and mortality can be incorporated in a CGE model on both the production and consumption sides. They are constructed for a single representative agent. To focus on the role of health and medical care, capital is omitted and labor is the only primary factor.

For reference, the simplest CGE model with no non-market goods or health effects is given by Model 1. U_1 is the agent's utility function, C is consumption of goods and services, J is leisure, L is labor, T is the agent's time endowment, and F_1 is the production frontier linking feasible bundles of consumption and labor. The parameters of the utility function determine the demands for C and J and hence the supply of labor. Income obtained from labor is used to purchase consumption goods subject to the usual budget constraint.

Model 1:

$$U_1(C, J)$$

$$L + J = T$$

$$F_1(C, L) = 0$$

In Model 2 we introduce the relationship between pollution and health effects. The utility function is unchanged but we now include variable S for reductions in the time endowment due to sick days and early mortality; E for emissions that degrade air quality; and M for mitigating expenditures to offset the health impact of E. M can include a wide array of averting behavior, including moving to an area with lower pollution, as well as medical care. In addition, we extend the production frontier to F_2 which includes E and M as arguments. Thus, production now uses labor to produce two desirable goods, C and M, but also produces one undesirable byproduct, E. We also add a health outcomes function G_2 which captures the feasible set of bundles of S, E, and M available to the agent. G_2 captures the impacts of both air quality and health effects into a function with dimensionality appropriate to the speciation of pollutants and regional and demographic disaggregation of the CGE model.

Model 2:

$$U_1(C, J)$$

$$L + J = T - S$$

$$F_2(C, L, E, M) = 0$$

$$G_2(S, E, M) = 0$$

Implicit in Model 2 is a willingness on the part of the representative agent to trade off consumption and leisure against expenditures on mitigating activities to reduce the risk of sickness or death (represented by S). In particular, G_2 captures the efficacy of mitigating activities in offsetting the impact of emissions while F_2 captures the cost of mitigation in foregone consumption and (through labor supply) leisure. However, because health status does not appear in the utility function, the agent doesn't care about it directly and is only concerned about health to the extent that it affects the time available for labor and leisure.

The VSL is another way of expressing the value of the marginal willingness to accept a small increase in the risk of death. When expressed as a VSL, it aggregates these values across the number of individuals who would need to experience the risk change for the expected number of deaths to be one. In this formulation, where one considers death as causing a loss of labor time, the VSL is measuring the amount of income required to compensate for the value of lost consumption caused by the lost labor time. Thus it will exceed the wage rate times lost hours, since it is an inframarginal measure of the value of a finite amount of lost consumption that would have been purchased with the additional income (see Section 4.2 as well).

Model 2 introduces the healthcare system in a fairly general way. Because mitigating expenditures like medical care (a possible component of M) do not enter the utility function, this formulation properly categorizes medical care as an intermediate good that produces a valuable good—more time for labor or leisure—and does not show up as providing welfare directly. That is, increased pollution will lower welfare through its effects on health, recreation, soiling of buildings and materials, etc. One way to reduce these effects is to redirect some expenditure from utility-producing goods to mitigating activities such as medical care, traveling further for air quality or water quality conditions that maintain the quality of the recreation activities, and more maintenance of durables affected by pollution. In this model, welfare losses arise from opportunities that could not be taken because resources were moved from utility producing goods and services to the mitigating activities. There may also be loss because the mitigation was not complete: the increase in sick days and mortality risks could not be completely prevented.

In a more elaborate formulation shown in Model 3, the representative agent could be represented as consuming (gaining positive welfare from) health and other goods. Variable H now indicates health status, and the utility function has been extended to U_3, which includes H as an argument.

The agent's time constraint and production function remain the same as in Model 2 but the health outcomes frontier has been extended to G_3, which includes H as an argument. Expenditures on mitigating activities can thus reduce S, increase H, or both depending on the nature of G_3.

Model 3:

$$U_3(C, J, H)$$

$$L + J = T - S$$

$$F_2(C, L, E, M) = 0$$

$$G_3(S, E, M, H) = 0$$

Note that health H is not itself a marketed good but is a result of the agent's choice of mitigating activities M and environmental factors E. Thus in this formulation, like in Model 2, healthcare (as a component of M) is an intermediate good used to produce health, much like gasoline is an intermediate good used to produce transportation services. Like the effect of improved fuel economy in reducing the amount of gasoline needed, reduced pollution will reduce the amount of healthcare expense needed to achieve the same level of health. Health could be highly correlated with sick days and mortality, but because it enters the utility function directly, the value that the individual places on it may exceed the value of consumption or income foregone in producing it.

However, as noted in Section 4.2, putting health into a utility function used in a CGE model implies some restrictions that may not be applied to estimates of WTP made outside such a model. The issues concern the basic assumptions associated with utility maximization which are needed to ensure existence of an economic equilibrium:

1. Total WTP for health increases with the amount of health consumed;
2. Marginal WTP for health is non-increasing in health at least locally (quasi-concavity);
3. WTP for health increases with income;
4. Total WTP is constrained by the household's budget constraint.

There is also the interesting implication that except in special cases, decreasing pollution will decrease mitigating expenditures such as health care (i.e., that reducing E will lead to a smaller expenditure on M). Thus, decreasing E in a general equilibrium model will produce lower values for the mitigating activities related to the health effects of pollution but greater welfare benefits (due to both increases in H and decreases in M) than a stand-alone health effects model would predict since the latter would usually hold healthcare expenditures constant. This is a very general economic principle but one that can only be captured with an appropriate utility specification.

No CGE models with Model 3's representation of the implications of air quality regulations for health outcomes are currently available off the shelf for use in benefit-cost analysis. The closest model would be the work discussed for analysis of the general equilibrium effects of air pollution in Europe [See Mayeres and Van Regemorter (2008) and Vrontisi et al. (2016). Soft linked models for the US are also discussed in Matus et al (2008) and Saari et al (2015)]. However, small aggregate models along the lines discussed here, with rough parameters for the connections among pollution, healthcare and health outcomes, could be constructed. Doing so would provide insight into the kinds of results that more extensive research and more careful parameterization would produce, and would possibly even provide some insights into how large effects could be.

There are further issues to be considered associated with the amenity effects of air pollution that have been estimated with hedonic models. The first step required to incorporate these effects in a CGE framework would require analysis of the assumption required to decompose the contributions of health and amenity motivations for the tradeoff measures estimated for improving air quality within a hedonic framework. That is, a hedonic property value model is a reduced form description of what the market equilibrium implies a household would pay for reduced air pollution associated with a residential location. The analysis does not isolate the sources for a household's willingness to pay more for these improvements. Assumptions must be added to describe how the tradeoff should be related to a preference function. EPA (2015b) references work by Sieg et al. (2004) who use a multi-market framework to evaluate how locational sorting in response to changes in air quality and the associated changes in housing rents would influence benefit measures for the improvement in air quality. This analysis did not attempt to distinguish amenity and health effects. The preference calibration logic outlined in Smith et al. (2002) would need to be adapted to consider the joint role of amenity and health effects.

4.5.2. Empirical research to support incorporation of indirect health consequences

Charge Question: Is there an empirical literature to support the incorporation of potential health consequences of regulation, outside of those directly associated with pollution?

A subset of the contingent valuation (CV) research has adopted the approach of describing the object of choice posed to respondents as "plans" to improve some aspect of environmental quality. See Richard Carson (2011) for a bibliography of CV studies. In these studies the focus is on framing questions that provide a credible description of a policy that survey respondents perceive as consequential. What can be derived is a measure of the tradeoff that would be made for the policy described as a plan. One complication is that it may be difficult to transfer findings from these studies to different contexts: the specific measure of the associated change in quality may be inconsistent with the needs of a different benefit analysis. Other support can be found in the quasi-experimental literature where regulation is treated as an external effect on behavior that is hypothesized to affect environmental quality.

There have been claims that regulations which have the macroeconomic effect of inducing unemployment or reducing incomes will also adversely affect health, and that this indirect effect should be included in benefit-cost analysis (citations to be added).[12] However, as noted by Stevens et al. (2015), aggregate mortality is actually procyclical, with death rates rising when unemployment falls during economic expansions. The authors attribute much of the procyclical mortality they observe to a general equilibrium effect: the increased difficulty nursing homes face when other employment prospects improve for relatively low-skilled workers. An additional, but considerably smaller component, is due to an increase in motor vehicle accidents during expansions.

It should be noted that if the most inclusive CGE treatment described above were adopted, the income effects of air quality regulations might be expected to offset part of the improvement in health status resulting from the improvement in air quality because of the income elasticity of demand for healthcare. This is a valuable insight that could come out of a CGE approach, but is more limited than claims that reductions in real income or loss of employment in and of themselves produce adverse health effects. If there were empirical estimates of the relation between changes in income and changes in health status, these could be used to incorporate income into the health outcomes equation as a separate causal influence.

In principle, unemployment could also be incorporated as an additional negative input to health outcomes, by adding unemployment to the health outcomes equation. However, unlike changes in income from some baseline, it is the rare CGE model that even addresses unemployment [see Rogerson (2015) for a discussion of some strategies in a dynamic macro setting and Goulder, Hafstead and Williams (2016) for an environmental CGE model that incorporates involuntary unemployment]. In all the formulations discussed here, changes in labor supply will occur in response to changes in real wages, thus implying that if the effect of air quality regulations is to reduce wage rates, they will cause a lower level of employment. Thus it would be possible to add "labor" measured by the amount of the time endowment devoted to labor activities to the health outcomes equation as a direct causal factor. Again, there would need to be some empirical estimates of the observed relationship.

If CGE models themselves could be formulated that produced some form of involuntary unemployment as a result of air quality regulations that cause industry shifts over time, then that unemployment variable could also be incorporated in the health outcomes function (assuming, again, that adequate empirical estimates of the health effects are available.)

4.5.3. Approaches for incorporating indirect effects

> *Charge Question: What approaches could be used to incorporate these additional effects? What are the conceptual and technical challenges to incorporating them?*

[12] There are several aspects of these connections. Some are discussed in the papers in a special section of the *Review of Environmental Economics and Policy* in the summer of 2015 entitled "Unemployment, Environmental Regulation and Benefit Cost Analysis."

Under what circumstances would the expected effects be too small to noticeably affect the quantitative results?

The conceptual and technical challenges discussed above are relevant to this sub-question. That is, the answer lies in detailing the logic associated with providing consistent links between the tradeoff measures recovered for morbidity with the tradeoff measures for risk changes. That is, the choices an individual makes to mitigate some health condition that is not life threatening can in principle reveal tradeoff information – e.g., resources allocated to reduce days of illness. When a morbidity effect is linked to an increased risk of premature death, the response to it may reveal information relevant to several tradeoff measures. Suppose for example that angina is a condition that causes discomfort and signals a higher risk of death from heart disease. Mitigating behaviors could include weight loss, exercise, and pharmaceutical treatments. Time and resources would need to be reallocated to these activities and treatments. Measuring the tradeoff for the risk reduction from the composite of actions requires an allocation of how much of the bundle of actions reduces risk, enhances other activities of daily living and reduces angina pain and discomfort. The parameterization of CGE models forces these issues to be confronted.

The most direct approach for addressing whether the effects are too small to noticeably affect the quantitative results arises when the analysis evaluates the sensitivity of the parameters of a CGE model to the inclusion or exclusion of these measures from the process of calibration that has been used to recover these estimates. More specifically the linkages between what has been estimated and the model define a set of moment conditions. Calibration is the process of solving the nonlinear equations associated with these moments for the free parameters of the model. The issue comes down to how sensitive the parameters of the "non-environmental" goods and services in the model are to the importance assigned to the specific environmental services being introduced.

4.6. Effects of Employment Changes on Health Status and Crime

Charge Question: The public health economics literature examines how shifts in employment result in changes in health status and crime rates. Can these changes from employment shifts be incorporated into a CGE model, and if so, how? If these positive and negative impacts from employment shifts cannot be incorporated into the CGE model, can they be reflected in the economic impact assessment, and if so, how?

In theory, the effect of employment on health and crime can be incorporated into a CGE model; however, doing so in a plausible and credible manner would go well beyond the frontiers of current knowledge and would require major investments in model development. Given these difficulties and EPA's limited resources, we do not advocate incorporating these effects at this time, either in a CGE model or any other economy-wide model. The fundamental issue is that the effects are the result of a complex multiple-link causal chain. Regulation affects employment; employment affects health and crime; and health and crime affect the costs or benefits of the regulation. None of the links in this chain is direct or simple to quantify.

For example, most CGE models explain the number of hours worked as the equilibrium of supply and demand in the labor market. These voluntary movements in hours are likely to have a very different impact on health and crime than changes coming from involuntary unemployment. Very few CGE models capture unemployment and long-term joblessness, so even this first link in the chain would put the model at the frontier of what is currently available. To our knowledge no CGE model considers the effect of employment changes on health or crime. Capturing this and then accurately valuing the resulting benefits would thus require a model that goes well beyond any that currently exist. For example, to capture the procyclical mortality discussed in Section 4.5 would require a detailed model of the impact of tight markets for low-skilled labor on mortality rates in nursing homes. Such a model would be difficult and very time-consuming to build, and likely so complex that evaluating the credibility of its output would be nearly impossible.

The lengthy and indirect causal chain required to link air pollution regulations with health and crime will be extremely difficult. In our view, the length of the causal chain suggests the effects are likely to be small. Modeling efforts should focus first on effects for which the causal chain is shorter and the links in the chain are more direct.

It might be possible to pursue a simpler analytical-general-equilibrium approach focused specifically on this issue. This would be much less resource-intensive and would provide an internally consistent approach to the issue. However, such an approach would still face the same problem with generating credible estimates and thus would at best be able to provide only an extremely rough and imprecise estimate. Nonetheless, EPA could pursue such research in an effort to understand whether this issue is potentially large enough to be relevant, in which case further efforts to include these effects in an economic impact assessment could be warranted.

4.7. Health Status and Changes in Relative Preferences

> *Charge Question: When individuals experience changes in medical expenditures, this changes the budget available to the consumer for other goods and services. However, the consumer could also experience changes in their relative preferences for these goods and services (e.g., outdoor activities) as a result of a positive or negative change in their health and/or life expectancy. Is this a change that could be captured in a CGE model?*

4.7.1. Medical expenditures and budget constraints

Reductions in medical care costs due to air pollution reductions are unlikely to be realized at the household level

We begin by raising a cautionary note about an assumption implicit in the first part of the charge question—that changes in ambient air quality directly impact individual budget constraints through changes in medical expenditures. Households covered by employer-provided insurance, Medicare, Medicaid, or policies purchased through exchanges established under the Affordable Care Act (ACA) will have out-of-pocket expenses that are only weakly correlated with actual medical costs. In 2012, private and public insurance paid 42% and 40%, respectively, of all health care spending. Only 14% of expenditures were out-of-pocket (Centers for Disease Control and Prevention, 2016 [Table 98]), and a fraction of the latter expenditures were made at the margin. Although reductions in air pollution could significantly reduce medical care costs for *some* individuals—provided that health status improvements are not transient, in which case these costs would be postponed rather than reduced—the bulk of any cost savings would accrue to private and public insurers.

In the long run, some savings to private insurers could result in premium reductions to insureds. However, employers, not employees, are the insureds in employer-sponsored health insurance markets. While it is possible that some employers would pass on to employees any premium reductions, it is unrealistic to assume that they will. Savings pass-through is most plausible in labor submarkets where employer demand is highly inelastic due to intense competition for uniquely valuable workers. At the other extreme, any savings to government insurers (e.g., Medicare, Medicaid, VA and Tricare) would reduce government outlays and not be passed on to program beneficiaries.

Therefore, the best place to look for consumers to potentially realize cost savings is the individual health insurance market, where at least in principle insureds are also purchasers. However, savings are unlikely to be realized there, either. Health insurance is an annual product covering only medical care expenditures borne during the plan year. Cost savings from reduced air pollution must occur during the plan year to be realized, but premiums during the plan year are fixed, preventing insureds from realizing them. To have any opportunity of realizing cost savings from a multi-year phenomenon like air pollution reduction, consumers must stay in the individual health insurance market over many years – i.e., not leave the individual market for the employer-sponsored insurance market or a government insurance program, or become uninsured – all of which are common experiences. For any individual insurance plan, savings from reduced air pollution would depend in part on its customer mix, but customer mix changes significantly from year to year due to changes in enrollment patterns. Even if consumers stay in the market, the market displays rapid churn from year to year. Finally, to the extent that purchasers in the individual market are subsidized, any realized cost savings would be attenuated by the premium fraction covered by subsidies.

Observing cost savings in the individual health insurance market may be impossible simply because of the market's extraordinary volatility, which appears likely to persist. For 2017, a 25% average premium increase is forecast for the second lowest-cost "silver" plan, which provides the baseline for calculating subsidies (U.S. Department of Health and Human Services, 2016 [p. 5]). Any savings resulting from reduced air pollution would be impossible to detect in such a baseline. This is compounded by instability in insurer participation and resulting loss of consumer choice. The number of counties with two or fewer insurers has been projected to increase from 15% in 2016 to 30% in 2017. Five states are forecast to have a single insurer serving every county (McKinsey & Company, 2016).

The individual insurance market may be better characterized as a government program with mandatory participation and substantial subsidies. As of December 31, 2015, just 6.8 million persons had obtained Health Insurance Marketplace coverage. Only 16% of them paid the full premium; the remaining 84% received substantial taxpayer subsidies in the form of advance payment of premium tax credits (Centers for Medicare and Medicaid Services, 2016). Therefore, only 1.9 million persons theoretically could have directly captured medical care cost reductions in 2015 resulting from reduced air pollution since 2014. But any such cost reductions would not be captured in practice, for at least three reasons. First, aggregate savings in the individual market would be trivial because actual beneficiaries would be rare. Second, it would be impossible to discern which of the roughly 2 million buyers actually experienced reduced medical care costs. And third, the ACA forbids insurers from passing on reduced costs to specific insureds even if they could be identified. Even if 100% of aggregate reductions in medical care costs properly attributable to air pollution reduction were passed on to consumers, individuals who did not experience significant improvements in health status from reduced air pollution would capture almost all of these cost reductions.

Significant health benefits from reduced air pollution are expected to be concentrated among persons who are elderly, infirm or both. EPA recently published two estimates of incremental avoided adult mortality for a $PM_{2.5}$ standard of 12 $\mu g/m^3$ (460 and 1,000 cases), and one estimate of avoided incremental infant mortality (1 case). EPA translated these incidence estimates into incremental dollar-denominated benefits ($4,000–$9,000 million for adults; $11 million for infants [$2006, 3% discount rate]) (US EPA, 2012 [Tables 5-18 and 5-19]). Further, EPA estimated that more than half of the expected incremental gain in life-years would accrue to persons aged 65+ (US EPA, 2012 [Table 5-23]). Benefits are disproportionately obtained by the elderly and infirm.

Elderly and infirm individuals are predominantly served by Medicare and Medicaid and would see little or no change in their share of the total cost of medical care even if cost savings were much greater than projected by EPA due to $PM_{2.5}$ reductions. Any cost reductions would be realized as reduced federal and state program expenditures, and thus a lower burden on taxpayers, rather than as lower costs to the individuals directly affected by air pollution.

Preference changes due to reductions in air pollution would be difficult to model and are likely to be minor compared to preference changes due to other factors

Although it is unlikely that persons who gain substantial, non-transient improvements in health status because of air pollution control will capture increased income from reduced medical care costs, these individuals could experience changes in relative preferences as a result of air pollution control-mediated improvements in health status. Formally, such individuals would have state-dependent utility functions.

As a theoretical matter, state-dependence could be incorporated into a CGE model via modifications to the utility functions used to represent individual behavior. However, parameterizing those functions would be difficult. As noted in a recent survey of the literature on health state-dependent utility (US EPA, 2015b) there is relatively little conclusive empirical evidence on state dependence. Estimating the parameters governing state dependency for use in a national-level CGE model would require historical preference changes that were observable, that affected a significant portion of the population, and that could be reliably attributed to non-transient improvements in health status resulting from reduced air pollution. But preference changes routinely occur due to a host of phenomena including age, family status, income and technological change, among others. Any effort to attribute observable, non-transient improvements in health status resulting from air pollution control must take account of myriad economic, social, technological and cultural phenomena (and changes in these phenomena) that also may change preferences. It is highly unlikely that the fraction properly attributable to reduced air pollution could be credibly identified amidst all of the other factors affecting state-dependent utilities.

Finally, there is no *a priori* reason to expect a disproportionate increase in demand for environmental goods and services such as outdoor activities. Indeed, improvements in health status could increase the marginal utility of consuming myriad other goods and services, including for example, other forms of medical care (e.g., joint replacements) considered more beneficial at the margin.

For all the reasons set forth above, additional work by EPA in this area is **undesirable**.

4.7.2. Likely magnitude of effects

> *Charge Question: Under what circumstances would the expected effect be too small to be of importance to the quantitative results?*

Two aspects of state-dependence that have been discussed in the literature are of potential importance. First, the marginal utility of overall consumption may depend on health status. To the extent that it does, it could affect money-metric measures of welfare such as equivalent variation. Second, as noted in the charge question, any cost savings that might be realized could change the allocation of expenditure across goods. While a large effect cannot be ruled out *a priori*, given the ambiguity of existing studies, at the national level both effects are likely to be small relative to other impacts of regulation, and quite likely unobservable in almost every circumstance.

With that said, it is plausible that reduced risks of non-transient deteriorations in health status properly attributed to reductions in air pollution might lead some individuals to reduce expenditures on averting behavior (such as through changes in the demand for real estate in areas with changes in air quality, which is discussed further in Section 4.11). The amount by which averting behavior would decline depends on a host of factors including intrinsic risk preferences, budget constraints, the relative prices of averting goods and services, and risk perceptions. Indeed, risk perceptions are key. Not only could perceived risk be greater or less than objective estimates of risk, but risk perceptions could be exacerbated each time the Agency takes an action that intensifies risk perceptions. For example, decisions to increase a cancer potency assumption, lower a Reference Dose, or reduce the threshold for presumptive adverse effects of a pollutant seem likely to induce additional averting behavior even in the absence of regulatory action.

4.7.3. Improving on the Section 812 approach

Charge Question: If this effect cannot be modeled, how can the approach to incorporating the change in medical expenditures, as employed in the Section 812 study, be improved upon?

In the Second Section 812 Prospective study (US EPA, 2011), reduced medical expenditures attributed to lower air pollution were calculated by extrapolating from published cost-of-illness estimates. These estimates were then interpreted as realized cost savings to individuals, with the amounts used as inputs in EMPAX-CGE (US EPA 2015b, p. 15). Implicitly, the 812 study assumed full pass-through by insurers to employers of reduced medical costs in the form of lower premiums, and full pass-through of lower premiums from employers to employees. As noted in Section 4.7.1, these assumptions are inconsistent with health insurance markets in which third parties are the insureds. Moreover, they were not validated by the Advisory Council on Clean Air Compliance Analysis during its reviews of the Second Prospective study (US EPA Advisory Council on Clean Air Compliance Analysis 2010a, 2010b, 2010c, 2010d, 2010e, 2010f). Minimal validity might be inferred from rigorous pre-dissemination information quality review, but the Second Section 812 Prospective and the Council's reports suggest that no such review was performed.

For these reasons, a preliminary step that should be taken before applying the 812 approach is to conduct a rigorous and transparent evaluation of information quality and the validity of the model's assumptions about the extent to which any cost savings realized by third parties would pass through to consumers. Moving beyond that to incorporate health state dependence in CGE models is **undesirable** because the magnitude of such effects will be highly uncertain given data limitations.

4.8. Incorporating Productivity Gains

Charge Question: Some potential benefits, such as productivity gains of the workforce due to cleaner air, are not typically quantified in either a CGE or partial equilibrium framework. Is there a sufficient body of credible empirical research to support development of a technique for incorporating productivity gains and other benefits or dis-benefits that have not been typically quantified into a CGE framework? If so, are there particular approaches that EPA should consider?

Potential benefits from productivity gains of the workforce due to cleaner air may be important to include in both CGE and PE models. However, the current state of the literature is such that there is not enough information about either the direct or indirect benefits that may exist. An important role that EPA could play is to encourage and support the collection, public disclosure and analysis of data that improves the understanding of the productivity effects of regulation and of cleaner air on the workforce.

In addition, clarification is necessary in determining what "benefits" should be included. Should only direct (productivity) benefits associated with changes in technology or process be included? Here, the existing literature provides only limited information, as most studies are industry, technology and/or worker-specific, so applying those estimates to the manufacturing sector (or the economy) as a whole would not be valid. If the productivity benefits are to include those that arise from the cleaner air itself, even more uncertainty exists. One way in which cleaner air may lead to productivity gains is through health benefits that can be translated to fewer sick days. This does not, however, capture benefits in productivity that may arise due to workers simply feeling "healthier" or "happier," and hence, more productive if cleaner air also means a reduction in lower-level measures of illness, such as headaches or fatigue.

There is little empirical work that tries to measure the direct benefits to productivity that may arise from cleaner air. One of the first pieces to try and tackle this issue directly is Zivin and Neidell (2012). In this paper, they examine daily worker productivity on a farm in California where workers are paid on a piece-rate basis picking blueberries and grapes. Worker "output" is easily measured in this context and the authors examine the relationship between daily worker productivity and ozone levels. Zivin and Neidell find that even at low levels of ozone, a 10 ppb change in average ozone exposure can lead to a statistically significant 5.5% change in average agricultural worker productivity. Along the same lines, Chang, Zivin, Gross, and Neidell (2016) examine worker productivity amongst pear pickers and packers where they compare productivity against a number of different pollution measures. They find that PM 2.5 has a significant effect on both indoor and outdoor workers (which would be expected as PM 2.5 can breach physical structures), but ozone (which cannot breach physical structures) only has a measurable effect on outdoor worker productivity. The authors suggest that there are significant welfare benefits that could arise from regulation of PM 2.5.

Gains to productivity also may arise indirectly through changes in both short-run and long-run health benefits. Measuring these benefits requires having a strong understanding of the relationships between health, productivity, and the environment. Unfortunately, these relationships are complicated and not well understood. A thorough summary of the economics literature examining this area can be found in Zivin and Neidell (2013). One of the most interesting and potentially important areas of research in this field looks at the relationship between air pollution and cognitive performance and its potential effects on human capital formation. One example of an indirect effect on worker productivity that can arise from changes in air quality is given by Lavy, Ebenstein, and Roth (2012). In their work, they examine the effects of air pollution on testing scores by Israeli students writing exams for their Bagrut certificate (a requirement for college entrance in Israel). They find that higher levels of pollution on test days are correlated with lower test scores. These lower test scores could lead to an inefficient allocation of students across schools and thus have long-run implications for human capital formation.

Indirect benefits/costs on productivity from air pollution, although potentially very important, are clearly more tenuous in nature and the state of knowledge may not be of a sufficient quality to be usefully incorporated into either an economy-wide or partial equilibrium model at this time. Given the shortcomings in current understanding of these issues, we recommend that EPA consider broad integration of productivity gains of the workforce into CGE models to be a long term objective. With that said, it would be appropriate for EPA to use high-quality peer-reviewed studies of industry-specific worker productivity in PE analysis when such studies are available.

4.9. Impacts on Non-Market Resources

Charge Question: Impacts on non-market resources are not typically incorporated into CGE frameworks, though research has indicated that these impacts could be important in this context. Is there a sufficient body of empirical research to support the development of techniques for incorporating these impacts into existing CGE models that may be available to EPA? What are the particular challenges to incorporating non-use benefits into a general equilibrium framework (e.g. non-separability)?

The parameterization of many CGE models relies on logic summarized by Rutherford (2002) that normalizes the prices of marketed goods to unity and measures the amounts of market goods and services (as well as factor inputs) relative to a numeraire. This process allows the distribution parameters in cost or production functions to be calibrated to correspond to the shares of expenditures for each sub-function and focuses the attention in parameterization on the elasticity parameters and the consistent construction of the Social Accounting Matrix.

When nonmarket resources are introduced into preferences or production functions as measures of negative or positive externalities, they must be treated as quasi-fixed from the decision-making agent’s (household or firm) perspective. This change implies that functions often assumed to be homogeneous become non-homothetic. Calibration is still possible, but there are many choices in how it is done. If one follows the Perroni (1992) logic, then calibration is based on the same basic approach used with purely market goods but with the shares defined in terms of shares of virtual expenditures—including the expenditures attributed to the nonmarket services. In these cases virtual prices must be specified consistently with the mechanism linking the amount of the nonmarket services to the external effects (e.g. pollution) of the production or consumption of marketed goods.

The details of implementing this logic have been outlined in theoretical and empirical terms.[13] Thus the process is understood and well vetted. When we introduce a measure of pollution or air quality (say Q) into a structural model capable of describing a general equilibrium (such as a CGE model) it might be introduced into the representative agent's utility function as:

$$U(G, L, Q)$$

Where G is goods, L is leisure time, and Q is air quality (negatively related to air pollution). The agent would have a budget constraint of the usual form, with income related to payments to factors, and so forth. Suppose M is income. Then the virtual price (or marginal willingness to pay for small change in Q) will be:

$$\pi = \frac{U_Q}{U_M}$$

where the subscripts designate partial derivatives with respect to Q and M. Let Q_0 be the baseline or initial level of Q, and let Q_1 be the new level, with $Q_1 > Q_0$. Then the following expression provides an approximate measure of the economic value of the improvement:

$$\pi \cdot (Q_1 - Q_0)$$

Since $\pi \cdot (Q_1 - Q_0)$ is derived from the utility function used in the model, if we set this equal to our measures for the economic value a person would place on $(Q_1 - Q_0)$ from partial equilibrium damage functions or other approaches we are implicitly applying something like the non-market equivalent of Irving Fisher's factor reversal test.

Espinosa and Smith (1995) described how nonmarket environmental services can be introduced into preferences through the threshold consumption parameters of a Stone-Geary specification. This strategy assumes there is a perfect substitution relationship with each of the commodities or services where the environmental service is assumed to influence a threshold parameter. It is the logic that implicitly underlies the strategy that EPA adopted in their CGE analysis in the Second Prospective Report (in Chapter 8) and the Mayeres and Van Regemorter (2008) work cited by EPA (2015a). However, the Espinosa-Smith work (summarizing Espinosa's (1996) thesis)

[13] The original issues associated with non-separability were discussed in an exchange between Diamond and Mirrlees (1973) and Sandmo (1980). While Cornes (1980) clearly documented the problems with the Diamond-Mirrlees arguments for imposing restrictions to preferences, including separability, most of the literature in public economics followed Diamond and Mirrlees. Discussions of non-separability in the context of second best analysis of externalities can be traced to de Mooij (2000). A demonstration of the empirical feasibility of including non-separable external effects was first reported using Stone-Geary preferences in Espinosa and Smith (1995) with the details of the CGE model developed in Espinosa's thesis (1996). Subsequent research by Schwartz and Repetto (2000), Williams (2002, 2003) has developed the conceptual issues in introducing nonmarket services into the second best analysis of the welfare effects of distortions. Carbone and Smith (2008, 2013) have demonstrated the feasibility of implementing the Perroni logic in models with several external effects.

incorporated all the feedbacks and the emission process. It did not adopt the "soft link" strategy of recent work.

Nonuse values by definition do not leave a "behavioral trail" or imply non-separability. There are a variety of strategies for considering their inclusion. Carbone and Smith (2013) suggest one that relaxes the full non-separability assumption.[14]

There are at least two issues with incorporating nonuse values. The first is discussed in Carbone and Smith (2013) concerning whether separability of the nonuse services is the only way to represent the effects of nonuse related motives for valuing the environment. This paper argues that "faint" behavioral traits might also capture what is intended by nonuse value. Revealed preference approaches to non-market valuation tend to focus on a single link between a private good and a nonmarketed environmental service. There may well be multiple private goods that are affected by the level of environmental services (see Kling(1989), Larson(1992). Some of these private goods might not be labeled as uses. Extending the calibration practices to consider multiple links between private goods and measure of quality should be explored in future research. In addition other uses of time may hold promise as faint signals. For example, Farrow and Larson (2012, undated) have also proposed the use of indirect indicators of nonuse values such as comparing television news viewing counts depending on the stories covered. They use the cases of the Exxon Valdez oil spill and the Gulf Oil spill to illustrate their arguments. A second issue relevant to incorporating them in CGE models is the "extent of the market" for nonuse values. That is, what fraction of the households in a given area (or economy) have positive nonuse values? The answer to this question is especially important for aggregate analysis because it determines the income (or expenditure) share used in calibration.

It would seem that the best strategy would be to start with incorporating use values for environmental services with non-separable preferences and include recognition of the feedback effects associated with the link between emissions of pollutants and the associated levels of the nonmarket services.

4.10. Interpreting Results When Some Benefits Cannot be Modeled

> *Charge Question: Relative to other approaches for modeling benefits, what insights does a CGE model provide when benefits or dis-benefits of air regulations cannot be completely modeled? How should the results be interpreted when only some types of benefits can be represented in a CGE modeling framework?*

A CGE model provides a consistent "accounting" framework because it imposes a balancing criterion between the sources of income and the uses of those resources in expenditures for all agents (i.e. households, firms and potentially government) that are represented in the model.

[14] See Herriges, Kling and Phaneuf (2004) for discussion of the challenges in using revealed preference information to estimate nonuse values.

Because these models are intended to depict market exchanges, this accounting framework includes conditions that assure price determination is consistent with budget balancing and with assuring that the quantity demanded equals the quantity supplied at each commodity's equilibrium price. Finally, when the models are constructed to represent perfectly competitive markets, CGE models maintain that agents take prices as given and implicit entry and exit conditions yield zero profit outcomes for all producing sectors represented in the model.

When the benefits (or dis-benefits) of the air regulations are introduced in the models with the added assumptions that they are due to non-separable services affecting preferences, production relationships, or both, then these added connections require the "accounting framework" to be reconciled with the benefit measures. Moreover, if the links between emissions and these non-market services are also included, then there is a further level of consistency to be maintained between the representation of economy-wide market outcomes and the benefit measures assigned to air regulations. If the benefit measures are incomplete, full consistency between the model and the economy will not be achieved. However, this does not imply that such a model lacks informational value. It can offer an important plausibility gauge and can serve as a basis for evaluating whether the general equilibrium effects of major rules are important enough to warrant modifying benefit-cost estimates developed using partial equilibrium methods. For example the early Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) analyses of the social costs of environmental rules included engineering estimates of the costs of environmental regulations to gauge the general equilibrium price effects of the size of these costs impacts across sectors. In the context of industrial organization analyses of the extent of competition residual demand models can be interpreted as general equilibrium demand analyses where the focus is on a few linked markets to judge whether one product has monopoly power (see Scheffman and Spiller (1987) and Willig (1991) for discussion of early uses of this logic). The use of an incomplete GE model to judge the impact across sectors of new regulations is an analogous application.

As a cautionary note, it may not be appropriate to add CGE and non-CGE benefits since they may not have been consistently calculated. Benefit-cost analyses should be very clear about the categories of benefits that are captured and those that are not. When some benefits cannot be modeled, it is important to frame the economy-wide results as capturing only a portion of total benefits while another portion remains outside the model. Table 2 of EPA's White Paper on Benefits (US EPA 2015b) displays a long list of benefits categories for which effects have been quantified and monetized as well as the categories and pollutants for which this information is missing. If this table typifies the standard practice at EPA to transparently display missing information, then we are reassured that the best practice is already being followed. A qualitative discussion of benefits or dis-benefits that were not modeled should accompany such a list.

4.11. Spatially Distributed Benefits

Charge Question: For some benefit endpoints, EPA takes into account the spatial distribution of environmental impacts when quantifying their effects on human *populations. In these cases, is it important to capture the spatial component of health or other types of benefits in an economy-wide framework? What would be the main advantages or pitfalls of this approach compared to partial equilibrium benefit estimation methods used by EPA?*

It is clear from US EPA (2015b) that, at a local or regional level, spatial sorting of heterogeneous households can have an important impact on the estimated benefits from improved air quality. Therefore, the first order of business is to capture these effects in the bottom-up estimates of benefits. This also raises the question whether such spatial sorting requires a general equilibrium analysis. We think it is fair to assume that changes in commuting behavior, wages and labor supply will be most strongly felt at the local level. At a national, or even state, scale, such spatial sorting is expected to have little impact on, for example, national labor supply. In the interest of prioritizing resources, we suggest that spatial sorting should not be addressed in an economy-wide welfare analysis. When resources are available, however, it could be included in local or regional CGE modeling and used in analysis of impacts. Sorting plays a role in distributional analysis but likely will not influence national benefit-cost calculations.

There is a broader question about adding spatial detail in EPA's national level CGE analysis. It is now quite common to differentiate certain endowments spatially in CGE models. For example, river basins are now broken out in CGE models of water. One typically begins at the grid cell and then aggregates up to the relevant level of detail. Continuing with the water example, it is useful to draw on a recent paper by Liu et al., (2014), in which the authors examine the economy-wide impacts of water scarcity. This is very similar to air quality regulation in that it raises costs in some regions but not in others. As it happens, in their follow-up to the 2014 paper, Liu et al., (2016) ask the same question that the SAB is asking of air quality models: What if one suppressed some of the subnational detail? How much would that affect key variables? Of particular interest is the case wherein Liu et al. drop subnational watershed detail (unified river basins **–** to be compared to the full model results). In this work, the authors find that:

> Impacts on regional production, employment and water use vary greatly between the two models, since national models don't produce any variation whatsoever at the river basin level. National impacts on production and trade are evident, but the impact on aggregate welfare is quite modest. If we are only interested in aggregate welfare, it appears that a nested modeling approach would be fully adequate. One could take the estimate of water shortfall from a biophysical model and apply it to the national (unified basin) CGE model in order to assess the national welfare impacts of water scarcity (Liu et al., 2016).

This leads us to make the following suggestion for future research, which would involve producing a comparison in the spirit of Liu et al., (2016) with an air quality application. That is, aggregate regional shocks and apply the aggregate shock at national level, comparing the national results with those obtained by running a fully disaggregated regional/subnational GE model. How much do the national welfare measures differ between these two approaches?

Turning from water to airsheds, would this analysis be more useful than state-by-state disaggregation? Or could it be done in addition to state level disaggregation? That is, air quality is determined at the level of the airshed, while state policies are made at the state level, and do not necessarily coincide with airsheds. Air quality regulations under the NAAQS are administered via State Implementation Plans (SIPs). In most states this process is further disaggregated geographically in relation to "attainments" areas. For example, California has several such areas, some of which are delineated along the lines of airsheds, such as the South Coasts Air Quality Management District (SCAQMD).

However, unlike watersheds that are based on a uniquely defined hydrologic unit codes established by the U.S. Geological Survey, airsheds are generally defined on an application-dependent basis, e.g., EPA's 2011 Cross-State Air Pollution Rule. For airsheds, the attribution of air quality levels to emissions sources can encompass distant states. In some cases, a state's contribution to its air quality can be as low as a 1% of total pollutant loading. These different levels of detailed, geographic data would need to be aligned between the state or regional level and a CGE model's data structure to allow for suitable benefit-cost analyses.

Another approach to the issue would be the use of CGE models that divide the US into sub-national geographic areas, such as states. Not only could these models differentiate health or other types of benefits in each region, but with adequate data they could capture geographic interactive effects, relating to labor force mobility and competitiveness across regions. The ideal formulation is based on primary data at the sub-national level (or a "bottom-up" approach) and also includes flows of goods and factors production between areas in a fully articulated manner, i.e., known origins and destinations. The tradition has been to refer to these as "interregional" models. However, given the difficulty of obtaining data, the models are often constructed on the basis of a "top-down" approach that "pools" imports and exports between regions, for example, and distributes them according to regional shares (see, e.g., Giesecke and Madden, 2013). An example of a recent multi-regional CGE model of the 50 US states plus the District of Columbia is the TERM-USA Model (2013). As is the case with most "top-down" models, this model omits many important regional and cross-regional distinctions. However, it can accommodate various differentials generated by EPA analyses across states relating to health and other considerations, and can trace their geographic interactions to the point that the whole (US total) is not necessarily the simple sum of the parts (simply adding up all of the state direct impacts).

5. EVALUATING ECONOMIC IMPACTS

5.1. Appropriate Use of CGE Models

Charge Question: CGE models often assume forward-looking rational agents and instantaneous adjustment of markets to a new, long run equilibrium (for instance, most assume full employment). A 2010 peer review of the ADAGE and IGEM models indicated that this is "probably a reasonable assumption as these models should be viewed as modeling scenarios out forty or more years for which economic fluctuations should be viewed as deviations around a full-employment trend." In this context and relative to other tools EPA has at its disposal (e.g., partial equilibrium approaches), to what extent are CGE models technically appropriate for shedding light on the economic impacts of an air regulation, aside from its welfare or efficiency implications? In particular, please consider the following types of economic impacts: [responses listed in subsections below]

5.1.1. General principles

There are a few guiding principles that should inform an evaluation of whether or not CGE models are appropriate to assess impacts from air regulations. First, policymakers should think carefully about the nature of the question being asked and select a model that is appropriate to that context. Aspects of a model that could affect suitability include degree of geographic, temporal and sectoral disaggregation, time horizon, expectations, types of impacts that can be forecasted, and policy instruments incorporated. Different CGE models are likely suitable to distinct lines of inquiry.

Second, as exhibited by the detailed review of extant CGE models in the EPA White Paper on Impacts (US EPA, 2016a), EPA should consider a suite of CGE models. And, all else equal, analysts should employ the simplest model that is adequate to address the question(s) being asked.

Third, EPA should not aim to use one model for all applications. In addition to choosing an economy-wide model that is appropriate to the question, it may be necessary to link two or more models into a unified modeling system. As discussed in section 3.6, this would likely manifest as a connection (or connections) between (among) a CGE model and one or more sector-specific, disaggregated partial equilibrium models or among a national model and regional submodels.

Finally, there is a balance between capturing detail and complexity and the transparency and tractability of the model. Transparency and reproducibility are particularly important when proposed air regulations are likely to be controversial, though both criteria need to be defined in terms of whether competent experts can understand and replicate results. Clear explanations in heuristic terms of why economic impacts take the form they do and sensitivity analysis that shows the model responds in theoretically correct and quantitatively reasonable ways to changed parameters can also increase confidence and identify potential errors.

5.1.2. Short and long run implications of energy prices

Many CGE models assume frictionless adjustments from a policy intervention or other shock, making them most appropriate to evaluate long-run responses. A potential shortcoming, therefore, of such models is the inability to reveal or incorporate short-run impacts. However, there is a standard set of techniques in the literature for building short-run dynamics into CGE models. For example, adding capital vintaging, adjustment costs and limited substitution possibilities between factor inputs to CGE models are all accepted ways one can limit the response of the economy to policy interventions in a way that is consistent with short-run outcomes. One technique uses information from disaggregated, typically partial equilibrium, models to inform CGE analysis (see, for example, Borhinger and Rutherford, 2008). As such, PE and CGE models should be viewed as complementary tools rather than substitutes.

The ability of CGE models to effectively capture short-run impacts of air regulations on energy prices depends on multiple factors. First, the form of the air regulation matters. It is conceivable for a highly aggregated model to detect short-run impacts of a uniform policy that, say, levies an equal fee on emissions of a pollutant no matter where, or from what sector it is released. However, current and especially recent policies are far more complex; the Cross State Air Pollution Rule (CSAPR) establishes multi-state trading zones that are likely to yield different prices for SO_2 and NO_x emissions. Such design features reduce the ability for highly aggregated CGE models to reflect short-run, spatially-resolved effects of policies on energy prices. Though CGE models will always be more aggregated than the real world and many regulatory policies, there has been a great deal of progress in building multiregional CGE models down to the census region, state and National Electric Reliability Region. Economy-wide models with such disaggregation include the MIT USREP model,[15] the DIEM-Electricity model of the Nicholas Institute at Duke University[16] and the NERA NewEra model.[17]

Aside from policy design, CGE models are limited in their ability to accurately predict energy price effects because of heterogeneity in the fuel mix of regulated sectors. Consider a hypothetical policy governing SO_2 emissions from the electric power generation sector. SO_2 discharges are produced, primarily, from coal. Thus, the mix of input fuels used by generators

[15] Sebastian Rausch and Matthew Mowers, “Distributional and efficiency impacts of clean and renewable energy standards for electricity” Resource and Energy Economics Volume 36, Issue 2, May 2014, Pages 556–585

[16] Martin Ross, "Structure of the Dynamic Integrated Economy/Energy/Emissions Model: Electricity Component, DIEM-Electricity." Nicholas Institute for Environmental Policy Solutions Working Paper 14-11. Durham, NC: Duke University. http://nicholasinstitute.duke.edu/environment/publications/structure-dynamic-integrated-economyenergyemissions-model-electricity-component-diem;

[17] W. D. Montgomery, S. Tuladhar, M. Yuan, P. Bernstein and A. Smith. “A Top-down Bottom-up Modeling Approach to Climate Change Policy Analysis.” Energy Economics, Vol. 31 (2009) Supplement 2.

will dictate the cost of compliance, and the pattern of incidence in energy prices. That is, areas in which power is produced by burning coal will likely show greater impacts whereas other regions in which power is generated by hydro, renewables, natural gas or nuclear will not. Regional and fuel disaggregation is present in many modeling systems used to evaluate air regulations, and the best practice in disaggregation should be followed when regional differences in cost and price impacts are to be expected. Moreover, it is not sufficient for a model to provide disaggregated outputs simply by sharing out results for a larger region. True disaggregation requires a structural representation of behavior, technology and prices at the chosen level of disaggregation.

An additional factor that may complicate the estimation of policy impacts on energy prices is the interactions between air regulations. An example of this is compliance with the National Ambient Air Quality Standards (NAAQS). Estimating the impacts on energy prices of a new or proposed policy will depend on the current attainment status (NAAQS) of particular counties and metropolitan areas. Because failure to reach attainment with the NAAQS results in more stringent emission reduction requirements (relative to counties in attainment), there is likely to be spatial heterogeneity in the degree to which a new policy will yield additional abatement and metropolitan areas. Because failure to reach attainment with the NAAQS results in more stringent emission reduction requirements (relative to counties in attainment), there is likely to be spatial heterogeneity in the degree to which a new policy will yield additional abatement and subsequent costs and tertiary effects on energy prices. Again, the point is that a judiciously chosen degree of geographic resolution is necessary to capture these impacts. Disaggregation beyond the resolution of economic data in order to match regulatory boundaries, for example, will provide no useful information about economic impacts. Since county-level data is insufficiently reliable and consistent to be used in economy-wide modeling, this suggests that judicious aggregation is required to minimize the first-order errors induced by mismatching air and political regions.

5.1.3. Sectoral impacts

The issue of aggregation in CGE models is central to an assessment of whether they can adequately capture impacts of an air regulation that vary by sector. There are certainly examples of CGE models that feature sector-level disaggregation. These are discussed in US EPA (2016a, 2016b). What comprises a sector is not a necessarily common across CGE models. For instance, US EPA (2016a) cites CGE models that include from 9 to 497 sectors. Regardless of the definition of sectors, estimates of highly detailed within-sector impacts (such as plant closings and openings) may require linkages to sector-specific (partial equilibrium) models. The value of CGE is modeling inter-sectoral impacts from an air regulation. And, the utility of a sector-specific PE model is estimating intra-sector impacts, possibly at the facility level. Therefore, a CGE-PE linkage can translate general equilibrium effects from policy into facility-level ramifications such as openings and closings and vice versa.

Spatial resolution is also related to the discussion of sectoral impacts. That is, the geographic distribution of industries within the economy is not uniform. Access to markets or to deposits of particular raw materials results in patterns of industry locations that are well known: the Rust Belt, the Corn Belt, Silicon Valley are all examples of this phenomenon. Impacts of air regulations such as compliance costs, resulting changes in product prices, and changes to employment are therefore likely to exhibit spatial signatures. These patterns are highly relevant as they also interact with demographic and socio-economic phenomena, which may affect welfare outcomes if utility is concave in income.

Synthesizing PE and CGE models happens with either one-way or two-way linkages. One-way linkage feed results from economy-wide models into disaggregated PE models. Two-way linkages allow for the disaggregated effects (impacts disaggregated along a dimension such as: industry classification, production technique, region, or demographic group) predicted by the PE model to then feedback into the CGE model. The linkage passes the results from the disaggregated model back to the economy-wide model and subsequently solves for the new equilibrium. Conceptually, two-way linkages are preferred. Of course, it is computationally simpler and lower cost to use one-way linkages. Whether or not employing one-way linkages is an acceptable approach depends on whether or not the modeler anticipates important interactions *between* the models, as well as budgetary and time constraints.

5.1.4. Impacts on income distribution

As noted above, a central issue concerning the suitability of a given CGE model to assess the effects of an air regulation is the model's degree of aggregation. In the discussion above, aggregation referred to the geographic and sectoral composition of the model. Here aggregation focuses on the income distribution. Analysis of impacts on the income distribution are important in light of both environmental justice concerns and rising inequality.

A highly aggregated model omits very important distributional effects. If workers are risk averse, even a policy that produces an equal percentage reduction in annual income will have welfare effects that are not uniform if workers start with different baseline incomes. If air pollution regulations repeatedly have disproportionately adverse effects on the same subpopulations, the relative loss they experience grows. To detect such heterogeneous effects, a model must decompose the workforce according to categories of baseline income.

Consider a prediction by a model of a 2% reduction in earned income. This is insufficiently detailed to adequately assess impacts; whether such a reduction were manifest across all working persons or is concentrated in one sector, state, or metropolitan areas are (of course) very different outcomes, particularly if the predicted 2% income reduction is an average that includes many households with no income reduction at all. A CGE model may detect and report such heterogeneous effects (see, for example, Rausch and Reilly, 2011). However, it needs to be designed in such a way that such impacts are revealed.

Distributional effects also depend on how broadly income is defined. One level of analysis works strictly with income earned in the context of the market economy: wages, salary, and income from capital assets. An alternative definition of income includes non-market components such as the value of leisure time, home production, consumption of natural capital, and adverse impacts from exposure to environmental pollutants (see Nordhaus and Tobin, 1972). Using a broad notion of income is especially important in the analysis of air pollution regulations as such policy interventions will impact exposure and, hence, this augmented definition of income. CGE models would, in principle, be able to accommodate such an income construct so long as (1) the components of augmented income are monetized, and (2) they are matched in aggregation according to the CGE structure. See Carbone and Smith (2008, 2013) for conceptual discussions of some of the issues involved in including non-market components of income into CGE analysis.

5.1.5. Transition costs in capital or labor markets

Air regulations may have particularly concentrated impacts in particular sectors of the economy because such policies often target distinct sectors, industries, or facilities. One clear advantage of CGE relative to PE approaches is the ability to uncover worker or capital transitions from a regulated sector to an unregulated or less regulated one. However, many CGE models assume that reallocations are costless. Yet it is obvious that such transitions often involve considerable and sometimes highly persistent costs. These costs may result from prolonged periods of involuntary unemployment, the need to retrain laborers if human capital affected by an air regulation is particularly specialized, and the heterogeneity of transition costs within the income distribution. Persons toward the bottom end of the income distribution are likely to be less able to adapt to job loss because of less accumulated wealth and low baseline human capital.

Transition costs in capital flows between sectors have long been included in CGE models that include adjustment costs in investment. Transitional labor costs have been included much more recently, including by Hafstead and Williams (2016), which employs a search model to reflect frictions in labor markets. Search costs lead to heterogeneity in transition costs that vary according to policy design (i.e., whether the policy is a tax or an emissions standard) and over the business cycle.

Additional labor market rigidities that would be difficult to capture in any model, whether CGE or PE, may be important for air regulations. In particular, workers may be especially resistant to change in labor markets associated with industries—coal mining, oil and gas extraction—where employment has cultural attributes that make it "a way of life." CGE models, and even most partial equilibrium models, will fail to sufficiently capture such frictions.

5.1.6. Equilibrium impacts on labor productivity, supply or demand

Broadly speaking, evaluating equilibrium labor market impacts is a core strength of CGE models and one of the most important benefits they provide relative to PE approaches. Labor demand at the sectoral level is endogenous and responds to changes in prices throughout the economy. Labor supply in most modern models is also endogenous and results from tradeoffs between consumption and leisure. In the medium to long-run equilibrium imposed in CGE models, real wages adjust to balance changes in demand with changes in supply.

With that said, there is considerable room for improvement. Almost all CGE models use a highly aggregated approach to modeling labor markets and do not distinguish between different occupational or skill groups. They do not have separate demands and supplies of labor by workers with different levels of education (say high school vs. college) or different skills (machinist vs. attorney, for example). To be clear, some models do include educational achievement when constructing the effective time endowment behind labor supply and also allow for exogenous wage differentials across industries (see Jorgenson, Goettle, Ho and Wilcoxen 2013, for example). However, models generally do not have endogenous equilibrium wage differentials between different groups, nor do they have endogeneity in educational or occupational choice.

In terms of equilibrium impacts on aggregate productivity, CGE models provide useful but incomplete information. In the long term, productivity results from three forces: a) increased educational attainment and human capital accumulation; b) capital deepening; and c) technical change. As noted above, CGE models do not currently include endogenous educational attainment so the first component is imposed by assumption. CGE results will thus fail to capture any productivity impacts of air regulations that would come about through changes in the amount of education workers choose.[18] In contrast, CGE models that are relevant for air regulations will all include endogenous capital accumulation and will thus capture capital deepening. The final component, technical change, varies across models. In some cases technical change is imposed exogenously. Those models thus provide endogenous information about only one of the three drivers of productivity: capital deepening. Finally, models in which labor or total factor productivity is endogenous (responding to prices and sometimes to explicit investment in research and development) provide endogenous information on two out of three of the drivers.

5.2. International Competitiveness

Charge Question: Concerns are sometimes raised that in response to a change in U.S. environmental policy some domestic production may shift to countries that do not yet

[18] The discussion here focuses on the long term drivers of productivity and abstracts from the direct effects of air quality on workers, which is discussed in Section 4.8

have comparable policies, negatively affecting the international competitiveness of energy-intensive trade-exposed industries and causing "emissions leakage" that compromises the environmental effectiveness of domestic policy.

5.2.1. Applicability of CGE modeling

Charge Question: Could a CGE model shed light on the international competitiveness effects of air regulations? If so, what types of CGE models are needed to evaluate its effects?

Competitive effects and emissions leakage resulting from environmental policy in the United States are very real concerns. International trade is relatively free, so any policy that causes production costs to rise can lead to a price-induced decline in consumption of the domestically produced good, depending on the relative substitutability of domestic and foreign goods. The impact on heavily-regulated trade-exposed goods will be larger, given the greater effect on domestic production costs and the relatively high exposure of the good to foreign competition.

Proper modeling of such an industry is necessary to provide an accurate estimate of the likely effects of any change in regulation. Historically, most CGE models have used the Armington (1969) assumption along with perfect competition to capture the stylized facts of two-way trade in the same sector while retaining computational tractability. The Armington assumption treats similar goods from different countries as imperfect substitutes for one another in international trade. Typically, a single sector's foreign goods are aggregated into a composite good using a single elasticity of substitution, and that composite good, in turn, is treated as an imperfect substitute for the domestic sector's composite good. The domestic-foreign elasticity is frequently taken to be half the foreign-foreign elasticity of substitution (see, for example, the GTAP model, as summarized in Hertel, 2013). Considerable skepticism over the Armington structure arises for large changes in relative prices, however, because Armington models exhibit significant hysteresis in the pattern of trade.

Other recent approaches, such as using the Melitz specification for heterogeneous firms (Melitz, 2003) offer the possibility of modeling heterogeneity of firms and their emissions, both domestically and abroad, potentially offering better alignment with the stylized facts about production technologies and emissions across firms. Modeling firm heterogeneity is at the frontier of trade modeling, and the initial indication from an examination of carbon policy is that the competitive effects and leakage depend heavily on the trade structure. For non-carbon air regulation, it is not clear that the trade impacts will be significantly different across the structures (Armington vs. Melitz). Independent of trade impacts, the consideration of firm heterogeneity can inform the heterogeneity in regulatory burdens across firms with different emissions intensities. Because regulatory impact analyses may emphasize impacts on small firms, it may be desirable to track the size distribution of affected firms. In general, the heterogeneity being explored in trade analysis is not confined to domestic vs. imported goods: many products are heterogeneous in the domestic economy even within narrow classification categories. In terms of trade structures and industrial organization more generally, the EPA should keep apprised of this emerging literature in the near term and consider developments that move beyond the Armington assumption and perfect competition for the longer-term.

At the other end of the scale, some industries produce relatively homogeneous goods and involve largely one-way trade that differs by coast: for example, the U.S. imports on one coast and exports on another, as we see in refined products trade. In these cases, the Armington assumption can greatly underestimate competitive impacts on the industry.

Another area of modeling that is potentially useful for assessing the indirect effects of air regulations is to employ CGE modeling frameworks that highlight the impacts on global supply chains. Air regulations in one (upstream) sector might reduce the competitiveness of that sector, but because of shifts in international sourcing, adverse economic effects on downstream sectors might be substantially mitigated (though with potentially significant distributional effects; see Section 5.1.4). Multi-region CGE models can help identify the channels for such effects. Depending on the nature of regulations, identifying such channels might be quite important.

One of the most important challenges to effectively employing CGE analysis of air regulation concerns proper sectoral disaggregation and alignment with the policy being analyzed. For example, as noted in Section 3.2, a researcher would likely find it challenging to evaluate changes to boiler regulation using a CGE framework. The regulation concerns a narrow portion of each of a highly diverse set of industries. On the other hand, new air regulations concerning the production of clinker in the cement industry would be more tractable: while special modeling detail and focus would need to be paid to the industry, the sectoral coverage of the regulation is far more tractable and contained.

Another unresolved point about leakage in CGE models is the degree of mobility of primary factors (labor and capital). Many CGE models assume these factors are perfectly mobile within a nation or region, but cannot move between nations or regions. Such models can overstate leakage to the degree that these factors can actually move between regions (Baylis *et al*, 2014).

In general, CGE modeling is more appropriate when dealing with economy-wide emissions issues, such as carbon dioxide emissions, where the emissions mechanism is well-defined and regulatory effects propagate broadly through the economy. For localized criteria pollutants, leakage elsewhere is generally not a domestic environmental concern, but the competitive effects of regulation still may be important. Unlike carbon dioxide, for most of the pollutants that fall under the National Ambient Air Quality Standards (NAAQS) program it would seem global leakage and even inter-industry leakage would be hard to trace in a CGE context given that emissions factors would not necessarily track with fuel usage. However, unlike carbon dioxide, international leakage is only a concern for transboundary NAAQS pollutants.

5.2.2. Tradeoffs with other modeling dimensions

Charge Question: Does accounting for international competitiveness or emissions leakage effects in a CGE model necessitate compromises in other modeling dimensions that may be important when evaluating the economic effects of air regulations?

A credible CGE analysis will necessarily include a representation of trade, and this existing representation of trade will necessarily have implications for shifts of production and emissions from each industry in each country. Thus, accounting for competitiveness and leakage need not detract from other modeling dimensions. To be more specific, the model will include a specification of regions of economic activity, which might be the US economy, state economies, subnational regions, or multiple countries. These regions must be linked among each other or to a parametric representation of the rest of the world. The model will be generally classified as a multi-region model or an open-economy model. Open-economy models approximate external (foreign) agent responses through import-supply and export-demand functions, while multi-region models use explicit representations of each region's production, consumption, and trade. With the necessity of representing trade in some manner, the competitive effects and at least rough indication of trade impacts are integral to either approach.

For many research questions that consider regulation of criteria pollutants, an open-economy approach can be appropriate. For other issues dealing with carbon policy, a multi-region approach might be necessary. In particular, when foreign regulation of carbon is coincidental to domestic regulation, the leakage and competitive effects depend on endogenous foreign-agent responses. See, for example, the emerging literature on the stability of coalitions in international environmental agreements, as summarized in Barrett (1994, 2012). While accounting for international competitiveness or leakage in a CGE model does not necessitate compromises in other modeling dimensions, it is important to use a transparent structure that informs the specific research question.

5.2.3. Other economy-wide approaches

Charge Question: Are there other promising general equilibrium models or methods to assess international competitiveness effects of regulations?

Overall, the Panel recommends CGE modeling as a key method for assessing international competitiveness effects and leakage. There are, however, examples of good commodity-specific PE trade models that also might be useful. CGE models often operate at a level of aggregation that dilutes the impacts at a more granular level. As a longer term objective, the EPA should consider the use of PE as a supplement or complement to more aggregate CGE analysis. PE trade models are appropriate as a supplement when the regulatory impacts are expected to be narrowly focused on a specific trade-exposed sector. A CGE approach is warranted when the regulatory impacts are expected to impact a number of sectors that are trade-exposed or are otherwise linked through input-output relationships, although PE models may still be useful in revealing higher-resolution trade impacts.

5.3. Criteria for Evaluating CGE Models Used to Assess Impacts

5.3.1. Overall criteria

Charge Question: Organizations outside the federal government have also used CGE models to assess the economic impact of recent EPA regulations. What criteria should be used to evaluate the scientific defensibility of CGE models to evaluate economic impacts?

The criteria for evaluating CGE models developed outside of the federal government should be the same as those applied to evaluate CGE models that are developed and used by government agencies themselves (US EPA, 2003). In addition to applicable information quality standards (OMB, 2002; U.S. EPA, 2002; OMB 2005), the basic checks for any CGE model include: a) availability, completeness and transparency of model documentation; b) public access to the model, including its source code and all other material components (See Section 3.3.1); c) a theoretically consistent structure based on microeconomic foundations that represents the behavior of producers and consumers; d) theoretically and empirically sound justifications for the choice of functional forms and parameter values; e) exploration of underlying reasons for any markedly different results from other models; f) peer-reviewed publications for the model or its closely-related antecedents; and g) substantial evidence of robustness with respect to alternative plausible assumptions, model specifications and data.

Models should be evaluated based on their comparative ability to answer the particular policy questions at hand. Among the factors that can be used are the following: a) the level of granularity needed for impact analysis (e.g., level of sectoral detail, the representation of regions, disaggregation of consumers by income groups); and b) the ability to capture interactions across markets, regions, and household groups.

Model performance should be tested via model comparison exercises and through simulations examining alternative assumptions, data, and sets of stylized facts. Reproducing history *per se* is not an appropriate measure to evaluate CGE models, due to the difficulty of identifying and modeling the large number of complex shocks impacting the economy over time. As noted by Chen et al., (2016), while individual parameters of the model can be estimated statistically or informed by econometric studies, the data needed to estimate the entire set of model parameters as a full system rarely exists. And, even where it is possible to estimate parameters of the model from data, often there are multiple candidate structural formulations of the model that may fit historical data well, yet the implications for projections can be quite different.

As with any other modeling approaches, CGE models can mislead more than inform if, for example, they convey a false sense of accuracy or precision. As discussed in detail in Section 6.4, when uncertainty is neglected and only point values are presented from a quantitative analysis, model results inappropriately imply greater confidence in those estimates than is appropriate.

5.3.2. Labor market impacts

Charge Question: What additional insights can economy-wide modeling provide of the overall impacts associated with a regulation, and in particular labor market impacts, compared to a partial equilibrium analysis?

A detailed discussion of the additional insights provided by economy-wide modeling approaches when evaluating social costs are available in Sections 3.1-3.2. The same considerations that are applicable for the cost analysis are valid for an analysis of economic impacts as well. Here, we briefly mention the major additional capabilities of economy-wide models: a) an ability to capture feedback effects from one sector of the economy to another; b) the inclusion of resource and budget constraints that allow them to provide useful reality checks in the analysis of policy; and c) a consistent and comprehensive accounting framework for adding up all the effects of a regulation, including all costs and all benefits.

In terms of the labor market impacts, economy-wide models have the ability to capture interactions across markets, regions, and household groups. CGE models consistently determine factor prices (including remuneration to labor) and capture factor price effects. Additional aspects regarding the insights and shortcomings of CGE models for labor market impacts are discussed in Sections 5.4 and 5.5.

5.3.3. CGE versus PE for comparing impacts

Charge Question: What are the advantages and challenges or drawbacks of using a CGE or other economy-wide modeling approach compared to a more detailed partial equilibrium approach to evaluate these types of economic impacts?

The advantages and drawbacks of CGE models for economic impact analysis are the same as advantages and drawbacks of these models for measuring social costs, which are discussed in Sections 3.1-3.2. Among the potential disadvantages of the CGE approach is its relatively aggregated structure, with less detail on each industry than offered by some engineering or PE models. In terms of labor market representation, as discussed in Section 5.1, existing CGE models usually assume full mobility of workers between sectors, and as such, they do not fully capture the real-world difficulties workers face from sectoral changes in labor demand. For example, CGE models might show that coal sector employment falls and information technology employment rises, but many occupations in those industries are different, and the difficulties of worker relocation and retraining are not represented. Thus, these models do not capture the full socioeconomic features of changes in sectoral employment.

Most CGE models assume full employment, include an endogenous labor supply decision, and only consider total hours of labor supplied. They usually do not distinguish between labor market participation and hours-worked decisions. As a result, it may be impossible to analyze labor market results with the degree of detail that might be necessary. For example, if a CGE model reports a three percent reduction in labor supply and demand, it is impossible to determine the extent to which workers leave the labor force or reduce their hours worked.

As with estimates of costs and benefits, an appropriate degree of foresight is important for evaluating economic impacts. As discussed in Section 3.2.5, the perfect foresight assumption has an advantage relative to other settings (e.g., recursive-dynamic) in modeling savings behavior. At the same time, a note of caution is warranted for intertemporal CGE models with perfect foresight (i.e., where economic actors have perfect information and knowledge of all policies for all periods of time covered by a modeling exercise). In addition to concerns about whether the assumption is plausible (especially for the long-term analysis), a model solution in this setting requires a simultaneous consideration of all periods of time, thereby increasing the dimensionality of the model. As a result, perfect foresight models represent substantially less detail of the economy than a CGE model in a recursive dynamic setting. A high degree of sectoral detail (especially in the electric power sector) required for air pollution analysis could lead to difficulties in finding a solution because of numerical issues in solving very large problems. Thus, perfect foresight models may have less applicability to estimate the impacts of very small policy or regulatory changes or in the settings where representation of substantial sectoral or household detail is needed.

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Models should be evaluated based on their comparative ability to answer the particular policy questions at hand. Among the factors that can be used are the following: a) the level of granularity needed for impact analysis (e.g., level of sectoral detail, the representation of regions, disaggregation of consumers by income groups); and b) the ability to capture interactions across markets, regions and household groups.

Model performance should be tested via model comparison exercises and through simulations examining alternative assumptions, data, and sets of stylized facts. Reproducing history *per se* is not an appropriate measure to evaluate CGE models due to the difficulty of identifying and modeling the large number of complex shocks impacting the economy over time. As noted by Chen et al., (2016), while individual parameters of the model can be estimated statistically or informed by econometric studies, the data needed to estimate the entire set of model parameters as a full system rarely exists. And, even where it is possible to estimate parameters of the model from data, often there are multiple candidate structural formulations of the model that may fit historical data well, yet the implications for projections can be quite different.

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Most CGE models assume full employment, include an endogenous labor supply decision, and only consider total hours of labor supplied. They usually do not distinguish between labor market participation and hours-worked decisions. As a result, it may be impossible to analyze labor market results with the degree of detail that might be necessary. For example, if a CGE model reports a three percent reduction in labor supply and demand, it is impossible to determine the extent to which workers leave the labor force or reduce their hours worked.

As with estimates of costs and benefits, an appropriate degree of foresight is important for evaluating economic impacts. As discussed in Section 3.2.5, the perfect foresight assumption has an advantage relative to other settings (e.g., recursive-dynamic) in modeling savings behavior. At the same time, a note of caution is warranted for intertemporal CGE models with perfect foresight (i.e., where economic actors have perfect information and knowledge of all policies for all periods of time covered by a modeling exercise). In addition to concerns about whether the assumption is plausible (especially for the long-term analysis), a model solution in this setting requires a simultaneous consideration of all periods of time, thereby increasing the dimensionality of the model. As a result, perfect foresight models represent substantially less detail of the economy than a CGE model in a recursive dynamic setting. A high degree of sectoral detail (especially in the electric power sector) required for air pollution analysis could lead to difficulties in finding a solution because of numerical issues in solving very large problems. Thus, perfect foresight models may have less applicability to estimate the impacts of very small policy or regulatory changes or in the settings where representation of substantial sectoral or household detail is needed.

5.4. Labor Impacts Under Full Employment Closures

Charge Question: What types of labor impacts (e.g., wage rate, labor force participation, total labor income, job equivalents) can be credibly identified and assessed by a CGE model in the presence of full employment assumptions? How should these effects be interpreted?

The vast majority of CGE models assume full employment: everyone who wants to work has a job, and wages adjust so that labor demand equals labor supply. This assumption is simple and transparent, which are major advantages. But it limits the labor impacts that a model can analyze in two important ways.

First, a full-employment model can't look at impacts that are directly related to full employment. Some implications of that limitation are obvious (for example, there is no unemployment in a full-employment model, and thus such a model cannot examine effects on unemployment). Other implications are more subtle: for example, a full-employment model could report the number of jobs, but the model's results for that number could well be substantially different from what a model without the full-employment assumption would report.

Second, in a standard full-employment model, the labor market moves immediately to a new equilibrium in response to a policy shock. Without full employment, that transition to the new equilibrium would take longer – perhaps substantially longer. Thus, labor-market results from full-employment models should be viewed as the long-run equilibrium of the labor market.

Beyond those limitations, there are some impacts that could in theory be credibly assessed by a full-employment CGE model, but would require model features that CGE models rarely include. For example, a full-employment model could look at labor market participation. But CGE models almost always model workers' labor supply decision simply as a single choice about how many hours to work, rather than as two (connected) choices: a labor-force-participation decision and a decision about how many hours to work conditional on participation. Specifically modeling the participation decision (which would be relatively straightforward to do, though very few CGE models have done it) would be necessary to credibly assess effects on labor market participation.

Finally, even for impacts that can be credibly assessed, one needs to be careful in communicating the results from a full-employment model to avoid misinterpretation. All labor market changes in a full-employment model reflect workers' voluntary choices. Thus, a policy-induced drop in hours worked in a full-employment model represents workers voluntarily choosing to work less (perhaps in response to lower real wages), not an increase in involuntary underemployment (workers who want full-time jobs but can only work part-time jobs) or unemployment. Voluntary changes have very different implications than involuntary unemployment or underemployment, and thus it is important to communicate accurately and clearly what the results represent.

One specific example is that CGE analyses using full-employment models should avoid reporting changes in hours worked in terms of "job equivalents" (where a full-time job equivalent is the number of hours worked by a full-time worker). The problem is that "job equivalents" are easily misinterpreted as "jobs", and thus voluntary changes in hours worked that are expressed as "job equivalents" are frequently misinterpreted as increases in involuntary unemployment. Expressing that result as a change in the quantity of labor or in hours worked provides exactly the same information, but is far less likely to be misinterpreted.

5.5. Modeling Transition Costs and Factor Market Disequilibrium

5.5.1. Recessions and labor markets

Charge Question: Are there ways to credibly loosen the full employment assumption to evaluate policy actions during recessions?

CGE models typically assume full employment: as with other markets in the model, the price (in this case, the wage) adjusts so that the quantity of labor demanded equals the quantity supplied (i.e., every worker who wants a job has one, and employers can hire as many workers as they want). Relaxing this assumption is rare in the environmental literature, but one can draw on work from other fields (especially labor and macroeconomics) to find methods for relaxing this assumption and to help evaluate the credibility of those methods in the environmental context. There are a variety of ways to loosen this assumption.

One simple way to relax the full employment assumption is to assume that the wage is forced to be above the market-clearing level, by either minimum wage laws or bargaining by strong unions. Because the wage is above the market-clearing level, more workers will want jobs than employers want to hire, thus creating unemployment. This is easy to implement, and might well be a reasonable model for a typical European country, but it seems like a poor representation of unemployment in the United States, where unions are relatively weak and minimum wages are too low to cause significant unemployment.

A second approach is to use a "Keynesian closure" rule for the labor market. This approach replaces the market-clearing assumption (that the wage adjusts so that the supply and demand of labor are equal) with an assumption that the wage is fixed and that the quantity of labor is determined by labor demand. In effect, this means that the overall level of economic activity is determined by aggregate demand, rather than by the interaction of demand and supply. Again, this is easy to implement. And it could provide a reasonable representation of the short-run effects of policy at a time when there is excess productive capacity (i.e., during a recession): if wages adjust slowly, then it's reasonable to think of them as fixed in the short run, and when there is excess capacity, supply constraints aren't binding and thus economic activity is demand-determined. But this would be a much less credible assumption over the longer run (when wages can adjust) and/or when the economy is not in recession (when supply constraints become more binding).

Moreover, the Keynesian closure assumption lacks clear microeconomic foundations (i.e., plausible microeconomic models of household and firm behavior that are consistent with the assumed market-level equations of a larger-scale model). The field of macroeconomics has moved strongly away from models without microeconomic foundations over the last few decades because of concerns that such models perform poorly at evaluating the effects of policy (the well-known "Lucas Critique"). Given that the purpose of environmental CGE models is to evaluate the effects of policy changes, the Lucas Critique would argue strongly against using modeling assumptions that are not consistent with microeconomic behavior.

A third approach is to represent unemployment as a stochastic process, estimated based on historical time-series unemployment data. This can provide good short-term forecasts, but it is difficult to endogenize unemployment under this approach – which is necessary in order to evaluate how policy changes might affect unemployment. This approach also lacks microeconomic foundations, and thus suffers from the same problems as other non-micro-founded models.

A fourth approach is to build job-search frictions into the CGE model. Under this approach, individuals who want to work don't immediately find jobs; instead, they must search for a job opening (and similarly, employers who want to hire must search for a worker to fill the job). This approach has several key advantages: it has realistic microeconomic foundations, it matches key stylized facts about the labor market (e.g., unemployment is never zero, even during economic booms, there is substantial job turnovers, etc.), and it is tractable to implement (though substantially more complex than the previous approaches mentioned). However, this approach is very new in the environmental context: to our knowledge, only two very recent environmental GE models use this approach (Aubert and Chiroleu-Assouline, 2015, and Hafstead and Williams, 2016). Thus, while this represents a promising approach, it may well not yet be sufficiently proven and tested in this context to be used for practical policy analysis.

Moreover, these models only consider one of the three major categories of unemployment. Those categories are frictional unemployment (unemployment due to workers moving or changing jobs), cyclical unemployment (unemployment due to downturns in the business cycle), and structural unemployment (unemployment due to a mismatch between the skills that unemployed workers have and the skills employers want). The two models mentioned above only consider frictional unemployment, not cyclical or structural. One could extend these models to consider structural unemployment by adding heterogeneity in skills among workers, though such an extension would be potentially difficult and complex. Extending the models to consider cyclical unemployment would be more difficult, because it would require introducing business cycles – an extension that would turn such a model into a DSGE model. Alternatively, one could work from the other direction, starting from an existing DSGE model designed to model business cycles, and extend it to model environmental regulations. Either approach would be challenging.

Thus, well-tested existing methods for relaxing the full employment assumption have serious limitations. New approaches are highly promising, but may well not yet be ready for practical use. As noted in section 3.1, we recommend that in the near term, EPA encourage further development of CGE models able to capture frictional unemployment. Development of models of structural unemployment should be considered a long term goal. Finally, we consider efforts by EPA to develop models for air regulation that include endogenous business cycles to be undesirable: given the current state of knowledge an easier and more transparent approach would be to apply sensitivity analysis to exogenous projections of business-cycle-driven unemployment.

5.5.2. Frictions and transition costs

Charge Question: Are there ways to credibly relax the instantaneous adjustment assumptions in a CGE model (e.g., add friction, add underutilization of resources) in order to examine transition costs in capital or labor markets such that it provides valuable information compared to partial equilibrium analysis or other modeling approaches?

One can obtain an initial rough estimate of how instantaneous adjustment affects CGE model results by comparing two polar cases, one with instantaneous adjustment and another in which the quantity of one or more inputs (e.g., capital and/or labor) is fixed. In a model with slow adjustment for a given input, the very short run will look like the case in which that input is fixed, and the very long run will look like the instantaneous-adjustment case (because even a slow-adjusting input will eventually adjust fully). Thus, this simple approach provides information about the very short and very long run results, but little information about the transition between those cases.

There are a variety of ways to go beyond that simple approach by explicitly modeling barriers to instantaneous adjustment. These are already widely used (though still far from ubiquitous) for modeling capital. These methods include capital adjustment costs (a cost to firms of adjusting how much capital they use in production), putty-clay models (in which new investment can be flexibly allocated across industries, but existing capital cannot be moved from one industry to another), and vintage capital models (in which existing capital is not only fixed in place, but also has characteristics such as productivity or factor intensities that are fixed at the time it is created).

Models with limits on labor adjustment are much rarer. Such limits could include the search frictions discussed in the previous section. One could also imagine a model with labor adjustment costs (analogous to the way capital adjustment costs are modeled), though to our knowledge no existing model includes such costs.

One could also model limits to price adjustments. Empirical work in macroeconomics has found strong evidence that prices are somewhat "sticky" – they do not adjust instantaneously – and that modeling that wage stickiness can help models in matching observed real-world phenomena. But results from those models are often very sensitive to the exact way price stickiness is represented in the model, and sticky-price models are often criticized as lacking clear microeconomic foundations (and thus potentially subject to the problems described earlier with non-micro-founded models). Price stickiness is very rare in environmental CGE models: the fixed-wage models described in the previous section can be viewed as an extreme version of wage stickiness, and Hafstead and Williams (2016) do some sensitivity analysis for wage stickiness.

5.6. Other Economy-Wide Approaches for Modeling Short Run Impacts

Charge Question: Are there other economy-wide modeling approaches that EPA could consider in conjunction with CGE models to evaluate the short run implications of an air regulation (e.g., macro-economic, disequilibrium, input/output models)? What are the advantages or disadvantages of these approaches?

Several approaches other than CGE analysis are frequently used to model the economic impacts of public policy in general and of air regulations in particular. These models are generally less well suited to benefit-cost analysis than to economic impact analysis because they typically lack the ability to estimate welfare changes. Most of these models are capable of analyzing the following aggregate and sectoral impact categories to various degrees at the national or regional levels: a) gross output; b) gross domestic product or value-added; c) personal income, employment, tax revenue, investment; and d) international or interregional trade. It is also possible to analyze distributional impacts by sector, socioeconomic group and geographic area. However, these models are not generally capable of addressing more micro-level economic impacts (e.g., effects on industries, facilities within an industry, competitiveness, suppliers and customers, profitability and plant closure; employment; energy supply, distribution or use; the operation of small entities, state and local governments, and non-profit organizations) or environmental justice effects (U.S. EPA, 2014 [Chapters 9 and 10, respectively]). Many of these limitations apply to CGE models as well.

The various alternatives to CGE models have different strengths and weaknesses. In the discussion below we will evaluate them according to the following criteria: accuracy, scope, degree of resolution (detail), flexibility, transparency, and cost.

5.6.1. Input-output models

In its most basic form, input-output (I-O) analysis refers to a static, linear model of all purchases and sales between sectors of the economy during a given time period, with parameters based on the technological relationships of production. This approach is often criticized because of its linearity, absence of a role for prices and markets, absence of input substitution possibilities, lack of behavioral content, and perfect elasticity of supply assumption. Research over years has improved upon the basic version, such that in principle an I-O model can be a dynamic, non-linear model of all purchases and sales between sectors of more than one economy, with parameters based on any major aspect of the kind that can be quantified and included in the underlying accounting system (Rose and Miernyk, 1989; Miller and Blair, 2009).[19] However, while many empirical I-O models incorporate one or two of these advances, all of them combined would render the model unwieldy (Rose, 1983). In essence, CGE modeling overcomes the limitations of the I-O approach while retaining its advantages: multi-sector detail, full accounting of all inputs, and focus on economic interdependence (Rose, 1995).

I-O models have been used extensively for nearly 50 years to analyze and estimate the economic impacts of air regulations (Leontief, 1970; Miller and Blair, 2009). This includes the construction of special-purpose models and the adaptation of government and commercial versions of these models, primarily at the regional level (IMPLAN, 2016; RIMS II, 2015). Unfortunately, the accuracy of these models is questionable because of the simplifying assumptions of the I-O approach, such as perfectly elastic factor supplies, which typically bias the models toward large impacts, even in the presence of cost increases associated with the purchase of pollution control equipment or forced inter-fuel substitution (Rose, 1983). Another consideration that limits the accuracy of I-O models is the fact that they are only generated with primary data every five years, and then with a 5-7 year lag between the year of release and the benchmark year, though time lags in data availability affect many other modeling approaches as well.

At the same time, I-O models do allow for a high level of sectoral detail (as many as 500 sectors), are easy to use, readily transparent (in that values and parameters can be depicted in simple tabular form), and very low cost to purchase from a commercial/government source. They are also somewhat flexible in relation to changing technical parameters.

Most applications of the I-O approach refer to the “demand-driven” version, where multiplier effects relate only to the upstream portion of the supply chain. This model is thus not complete, because it lacks the ability to track downstream impacts, such as the consequences for the customers of directly affected industries. A variant, known as the “supply-driven” I-O model has been developed to address this missing ability, and attempts to do so with a simple manipulation of the basic I-O table. However, some controversy exists over the legitimacy of this approach, which mimics Say’s Law (supply creates its own demand, though this is only a serious problem when an expansion of the economy is the outcome) and the lack of “joint-stability” of the demand- and supply-driven model parameters (Oosterhaven, 1988; Miller and Blair, 2009).

5.6.2. Social accounting models

[19] This originally included all non-market effects either because of the difficulty in quantifying them or their absence in national regional economic accounts. Much progress has been made on both problems.

Models based on social accounting matrices (SAMs) are similar to I-O models in their basic form: they are linear and represent basic accounting systems. However, SAMs extend the accounts to include savings, operation of business enterprises as sectoral aggregates, and various institutions that represent more detailed operation of government, trade, and international capital flows. In essence, the SAM approach retains the intermediate goods portion of the I-O table but extends the analysis to include a much broader set of economic accounts. Moreover, while I-O models focus on the physical movement of goods between sectors, SAMs focus on the counterpart flow of funds receipts from these transactions (Pyatt, 1988; Miller and Blair, 2009).

SAMs alone have not been used often to estimate the impacts of air regulations, and their use is primarily related to income distribution analysis or the extension of accounts to include natural resource and environmental balances (citations to come). The most prevalent use of SAMs is actually to provide the core database on which many CGE models are built (in terms of calibration and balancing so as to be consistent with a broad set of regional or national accounts). The evaluation of SAMs as a stand-alone analytical tool is similar to that of I-O models because they have so many features in common. Here, accuracy is also limited because of the assumption of linearity, though SAMs do include primary factor balances that can overcome some of the limitations of the perfect elasticity of supply assumption. Again, the SAM is readily transparent, though more complicated than the I-O production accounts, relatively easy to use, and very low cost from commercial sources. SAMs are also somewhat flexible in relation to changing technical and institutional parameters.

5.6.3. Econometric models

The essential input into the creation of an econometric model is a data set that describes the historical behavior over time of variables of interest. The set of variables is first divided into the endogenous variables, whose behavior is the focus of the model, and the exogenous variables, whose future values must be determined before the model can generate a forecast. An econometric model is a way of summarizing the conditional distribution of the endogenous variables given the exogenous variables.

The division between endogenous and exogenous variables is a judgment call based either on beliefs about causal orderings or beliefs about stability of parts of the system. For example, a short-term interest rate may be treated as endogenous if the historical record can usefully be relied upon to predict the future choices of the Federal Reserve, or can be treated as exogenous if the analyst considers the historical rate setting a poor guide to future rates and prefers to insert her own interest rate projections into the forecast.

For a what-if policy analysis, the relevant policy variables are treated as exogenous, but they may not have been so historically. A critical assumption of an econometric model used in policy making or forecasting is that the distribution of the endogenous variables conditional on the exogenous variables is the same in the future as it was in the past, and is thus invariant to the change in policy regime that policy interventions necessarily entail. When this assumption seems doubtful, analysts can search for surrogates for the hypothetical policy change. (These surrogates are usually called instrumental variables.) For example, although the Federal budget deficit is surely endogenous, the occasional wars that the United States has engaged in could be considered an exogenous randomized treatment, and the rise in the Federal deficit coincident with a war might help to form an opinion about the likely effect of a fiscal stimulus following the Great Recession.

Different adjectives are applied to econometric models depending on the list of variables included and the data studied. Though macro-econometric models used in forecasting typically include hundreds of variables, the four critical variables in a macro-econometric model are growth of real GDP, price inflation, interest rates and unemployment. The difference between PE and GE modeling comes either from the data studied or the variables included. A study of behavior over time at a single location can pick up the short-run PE effects, but a study that compares different locations at a single point in time can pick up long-run GE effects. For example, we can see how the Mexican economy evolves as its work force grows (short run), or we can contrast the structure of the labor-abundant Mexican economy with the less labor-abundant US and Canadian economies (long-run). Alternatively, GE models can have more endogenous variables than PE models, allowing, for example, capital and labor to shift between industries and locations, or allowing the accumulation over time of human and physical capital.

One important aspect of the econometric approach is that the model defines the optimal mapping of sample moments into the model's estimated parameters using the estimation approach known as maximum likelihood. The relevant sample moments include both contemporaneous correlations and intertemporal correlations. To express this differently, "calibration" in the econometric tradition is theory-driven, not ad-hoc as in most CGE models. A second important aspect of econometric modeling is that it has built-in, automatic humility: if the data are not available or if they are too weak to allow reliable estimates, then the approach spits out a warning that says, in effect: "These data do not allow us to answer that question." This warning is reflected in the standard errors applied to policy coefficients and forecasts, which are large when the data is weak. There is no comparable automatic humility in the CGE exercise. If policy makers want a feature in a model, a CGE model builder often will find a way to include it even when supporting empirical evidence is very weak. However, a well-designed study of the sensitivity of conclusions to changes in the model's parameters could supply the requisite humility.[20]

A third important aspect of the culture of econometric modeling is the pressure it creates to find evidence on which public policy can be reliably based. For setting the minimum wage, for example, a supply and demand framework is not enough. It is also not enough to calibrate a supply and demand model and study what that implies about the effects of minimum wages.

[20] Incidentally, honest humility may be the kiss of death for econometric models since they quite often produce uncomfortably wide error bands. In particular, longer run effects are typically difficult to estimate reliably with time series data because the longer-run "experiments" embodied in most time series are very weak.

What is needed are data collected in actual cases in which minimum wages were increased. Parenthetically, neither tradition does very well in providing an answer to a critical question: "What feature of the data allows you to form that opinion?"

Macroeconometric models have been used to analyze air regulations for nearly 50 years (see, e.g., Evans, 1973). One of the key advantages of econometric models is their forecasting ability. On the other hand, they are subject to the Lucas critique. While econometric data analysis is sometimes the basis for estimates of parameters used in CGE models, econometric estimation of the overall models with environmental effects included is rare, which may be because of poor natural experiments. For example, with all the other things affecting the Los Angeles economy, the impact of air quality regulations may be hard to detect. An exception is the simple econometrics of the environmental Kuznets curve (e.g. Grossman and Krueger, 1993).

Rather than thinking of econometric modeling as an alternative to CGE modelling, it may be better to try to combine the two cultures, using the better features of each.

5.6.4. Hybrid models

Several hybrid models have been applied to air regulations. Most of them are some variant of what is typically referred to as a conjoint input-output/econometric model. The simplest version is an I-O model with an econometric forecasting equation (or set of equations) appended to it (see, e.g., Rey, 1998). More sophisticated versions perform some econometric estimation of I-O model components or more fully integrate the econometric forecasting equation(s) with the I-O component. One of the most advanced of these is the INFORUM-Lift Model, which contains a 110-sector I-O component (a 360-sector version, known as Iliad, is also available, as are regional versions for all 50 states) (INFORUM, 2016). The INFORUM-Lift Model has been used to analyze the employment impacts of the Clean Power Plan (IEA/IER, 2015; see also the application to an OSHA rule by Werling, 2011). Overall, the assessment of these conjoint I-O-econometric models is they offer only a modest improvement over the I-O models presented above. Forecasting ability is a plus, but this does come at a higher cost.

The most widely used version of a hybrid model is the Regional Economic Models, Inc. (REMI) Policy Insight+ Model (a transportation version known as Transight is also available). It is summarized here explicitly because it is so widely used at the regional level (primarily by state government analysts) to examine a broad range of policy issues, including ordinary air regulations and climate action plans (see, e.g., Wei and Rose, 2014).

The main REMI Model is actually a hybrid of several modeling approaches. At its core is either an 80-or 179-sector I-O model. Beyond that, sectoral Cobb-Douglas production functions of labor, capital and energy are estimated on the basis of historical data, and time series data are also used to develop a forecasting capability for several macroeconomic indicators. In addition, the demographic (migration and labor supply) module more closely resembles a CGE approach, and is also based on econometric estimation of time series and cross-sectional data. More recently, the model has incorporated features reflecting economic geography with a focus on interregional competitiveness. Several studies have been undertaken to assess the forecasting ability and accuracy of the REMI Model and have indicated that it performs well (Cassing and Giarratani, 1992; Rose et al., 2011). At the same time, a major feature of the model relating to the estimation of impacts stemming from improvements in amenity values has come under strong criticism (Smith, 2015). The model is broad in scope and does provide a good amount of sectoral detail. It is not flexible in the sense of analysts being able to change its internal equations, nor is it entirely transparent because of its proprietary nature (even its equations in mathematical form are not transparent because of their complexity and because of the eclectic nature of the various modules). As a result, it is difficult to assess the logical coherence of the economic principles guiding its outcomes and it runs afoul of information quality standards.

CGE models, in contrast, take their logic directly from the theory of general equilibrium, ensuring that basic economic accounting identities are upheld and representative individual firm or household behavior is consistent with a rational decision-making process. The REMI model does, however, appear to have an advantage over other modeling approaches in its ability to handle regulations that are non-price-responsive through its facility to incorporate various types of technological change and changes in costs stemming from regulations (Wei and Rose, 2014).

5.6.5. Dynamic Stochastic General Equilibrium Models

Dynamic stochastic general equilibrium (DSGE) models are closely related to CGE models. Both are economy-wide models, with factor endowments, representative agent(s) maximizing utility and firms maximizing profits, budget constraints, the standard circular flow of income and goods, and market clearing conditions that determine equilibrium prices and quantities. Tastes and technology can be exogenous to the model or can evolve over time. Thus in principle DSGE models share the desirable characteristics of CGE models for evaluation of welfare impacts of policies.

Most CGE models lack a financial sector or monetary authority, whereas analysis of these markets is one of the primary purposes of DSGE models. DSGE models are characterized by three blocks of equations, one representing demand for goods and services, one representing supply of goods and services, and one representing monetary policy.

As in the case of CGE models, these equations are based on explicit assumptions about the behavior of households and firms, but DSGE models introduce additional assumptions about the behavior of government, in particular how the monetary authority reacts to inflation. The general equilibrium feature of the DSGE model involves households, firms and government interacting in markets that clear in every period. Since DSGE models include money as an additional commodity, market equilibrium conditions determine prices uniquely[21] so that

[21] Recall that CGE models without money determine only relative prices.

inflation is represent explicitly.

Unique features of DSGE

Where the approaches differ is that CGE models operate under certainty[22] whereas DSGE models incorporate uncertainty in the form of random shocks to any or all of the parameters that determine market equilibrium outcomes and represent households, firms and government as making decisions under uncertainty. These could include shocks to household demand, technology, prices and monetary policy.

Without these shocks, a DSGE and CGE model with the same structure would produce identical deterministic growth paths for the economy with neither surprises nor cycles. With these shocks, DSGE models become a tool for analysis of business cycles and how monetary policy affects the real economy and inflation.

As one survey article puts it, “The dependence of current choices on future uncertain outcomes makes the models dynamic and assigns a central role to agents’ expectations in the determination of current macroeconomic outcomes.”[23]

DSGE models replace the CGE assumption of perfect foresight by an assumption of “rational expectations” as an equilibrium condition. Under rational expectations, agents (households and firms) are assumed to know the probability distribution of random shocks and assign to future prices the same probability distribution as emerges from the DSGE model.

Thus, and this is the central focus of DSGE models, the rule that the monetary authority follows in reaction to observed inflation derived from the supply and demand blocks of the model sets expectations about future interest rates and inflation. Those expectations then modify behavior of firms and households, and the rational expectations equilibrium is found when the expectations of households and firms, together with the monetary authority rule, are consistent with distribution of market equilibria in each period.

A common rule for representing the monetary authority has the monetary authority raising nominal interest rates in response to observed deviations of inflation from some baseline. This then triggers a slowing in output growth which reduces inflation until it falls below the baseline,

[22] CGE models employ different assumptions about how much knowledge agents have of future state, ranging from expectations that current prices will persist forever or perfect foresight of prices in future periods. An extension of CGE models is to include contingent claims markets in which agents can execute contracts for all possible future states of the world. In these models agents are uncertain which state of the world will occur but execute contracts simultaneously at time zero that cover all possibilities. DSGE models assume that there are not complete contingent claims markets for every commodity and possible state.

[23] Argia M. Sbordone, Andrea Tambalotti, Krishna Rao, and Kieran Walsh Policy Analysis Using DSGE Models: An Introduction FRBNY Economic Policy Review / October 2010 pp 23 -

at which point interest rates are increased and so on. Thus the monetary policy rule generates a business cycle.

Use of DSGE models

As this description should suggest, the solution algorithms for DSGE models are not as straightforward as those for CGE models, and typically they involve solving a first or second order Taylor series expansion around the steady state. The first order solution treats all agents as maximizing expected utility, while a second order solution introduces some degree of risk aversion. Open source software is available for formulating and solving models of this type (www.dynare.org.)

DSGE models of this type have been used in the academic literature to study effects of monetary policy, and the formulation described above has been found to explain past cycles well. Moreover, choice of different variables to represent shocks to the economy have served to identify the events that have caused past economic fluctuations and how the shocks work their way through the economy. (Sbordone, et al. 2010)

DSGE models are commonly formulated to incorporate transition costs or markets with sticky prices or wages, so that a shock to the economy can have short run effects distinct from long run effects. In particular, involuntary unemployment can be introduced into a DSGE model in a conceptually more satisfactory fashion than in a CGE model where all markets are simultaneously in equilibrium.

Because of their ability to trace the effects of shocks through the economy, DSGE models have been used to analyze the short term impacts of other policy changes, such as tax policy. For example, a sales tax on certain goods will raise nominal prices and will shift demand among those goods, while an increase in the labor tax will be a combination of a price and a productivity shock as labor and capital are used in less optimal combinations.

Introduction of air quality regulations into DSGE models

Since DSGE models have the same microfoundations as CGE models and in particular are commonly used to investigate effects of price and productivity shocks, the costs of regulation could be introduced in similar ways. That is, based on engineering studies that estimate the cost of a regulation for a particular industry, the productivity of that industry could be reduced in order to generate a cost shock equal to the estimated cost of the regulation. Or, if the regulation involved constraints on choices of inputs that were modeled explicitly in the DSGE supply block, such as the mix of fuels used, then such a constraint could be introduced explicitly. For example, a carbon constraint could be introduced to induce changes in fuel mix or total fuel consumption.

To represent air regulations, the policy shock would have to be introduced as a permanent one. In principle, a regulation could be introduced as a known cost change pre-specified in every future period or it could be introduced as a random shock with an expectation equal to the estimated cost and some distribution around that cost. The former approach would: (1) allow for more simple solution algorithms to be used, since it would represent a change in expected values only and (2) provide estimates of how introduction of such a policy could affect near-term inflation, unemployment and GDP as well as the longer-term growth trend. The latter approach could provide a way to understand how uncertainty about future costs or about future changes in policy would affect current compliance decisions.

DSGE models would also provide perspective on how implementation of regulations at different points of the business cycle might affect their overall cost and whether they would have a benign or harmful effect on inflation and/or unemployment.

Availability of DSGE models

Off the shelf DSGE models suitable for modification along the lines discussed above are available, but not as commercial products. An open source framework for writing, estimating and solving is widely used by practitioners, and documentation, existing models, and software are available at www.dynare.org. The standard business cycle or monetary policy models available there could be used to capture transition costs and unemployment with less effort than developing new generation of CGE

However, there would be a tradeoff in the lack of sectoral and structural detail on the industry side and ability to incorporate policy-specific externalities such as health effects on the benefit side. However, the latter is less an issue because the advantage of DSGE over CGE is its ability to investigate transitional effects on employment, inflation and output beyond the capability of the DGE or econometric models.

Should EPA adopt DSGE models?

DSGE models provide the most advanced tools for analysis of short term impacts mandated for inclusion in regulatory analysis, including unemployment, transition costs, and inflation.

The Arrow-Debreu foundations of DSGE models make them an enhancement of CGE modeling approaches in this regard, rather than an alternative lacking the properties that allow consistent welfare measurements. This supply-side feature and immunity to the Lucas critique make them superior to econometric macro-forecasting models.

They also provide a consistent framework for assessing the impacts of regulatory uncertainty on aggregate investment and business behavior. At the same time, their lack of structural or technological detail makes it impossible to examine how more specific abatement decisions would be affected by regulatory or other uncertainty.

Estimated DSGE models can provide data-driven confidence intervals as well as those derived from assumed probability distributions.

Although commercial vendors do not now offer DSGE models, the software tools for constructing them are readily available. Purpose built or even existing DSGE models could be utilized for estimation of short run impacts discussed above by modifying cost and productivity parameters to reflect estimates from engineering or partial equilibrium models.

This is likely the highest and best use of DSGE models, since at present their computational requirements and complexity preclude incorporating the interindustry and technology detail possible in CGE models or a utility-based representation of health and related benefits.

Since both health effects of pollution and outcomes of improved air quality and medical expenditures are all uncertain, SDGE is an attractive approach to bringing the analysis of costs and benefits of air quality regulation into a common framework. However, much groundwork needs to be done on the basic representation of benefits in GE models before this additional step could be taken.

5.6.6. Summary

There is no single best model for all applications. As such, the analyst should select a model (or set of models) based on the level of aggregation and sectoral scope that is most appropriate for the particular application. In addition, the criteria of accuracy, transparency and reproducibility should inform the choice of models. The following general conclusions emerge from the assessment above:

I-O and SAM models have severe limitations that render them far below the current state-of-the-art in comparison to CGE and macroeconometric models. Perhaps the only application of the former two modeling approaches would be to cases of very short-run impacts of a relatively small nature, where substitution possibilities would be limited and price effects would be minimal. At the same time, both I-O tables and SAMs continue to serve as valuable databases for CGE models and for macroeconometric models with extensive sectoral detail.

Macroeconometric models have several relative advantages over other types of models. They typically model macroeconomic behavior with regard to aggregates such as consumption and investment better than other modeling approaches. They are based on more extensive data and their estimation lends itself more readily to the evaluation of model precision. Finally, they are able to forecast major aggregate and sub- aggregate variables.

Hybrid models, which generally add a forecasting capability to I-O, SAM, and, in a few cases, even to CGE models, are worthy of consideration when a forecast of the future baseline is needed, and, in more sophisticated versions, when interactions between forecasted variables and policy variables are especially important. At the same time, one must weigh this advantage against limitations of the former two modeling approaches when they are a major part of the "conjoined" models.

Overall, any modeling approach or individual model to be used by EPA in the future should be carefully vetted. This includes models typically used at the regional level are applicable to the national level and vice versa. If failings are identified decision need to be made carefully about whether improvements can be made to raise each model's abilities to meet the EPA quality standard.

Note that we have omitted the following models from our assessment: Agent-based models are not evaluated because they typically are not economy-wide; systems dynamics models have rarely been used to estimate the impacts of air regulations, though we refer the reader to an attempt to translate CGE analysis into a systems dynamics format (see Smith, 2016); and microsimulation models which are usually not economy-wide.

6. CONSIDERATIONS FOR ECONOMY-WIDE ANALYSIS OF AIR REGULATIONS

6.1. Technical Merits and Challenges

6.1.1. Overall value added relative to partial equilibrium approaches

Charge Question: Compared to other modeling approaches at EPA's disposal, what are the technical merits and challenges of using economy-wide models to evaluate the social costs, benefits, and/or economic impacts of relevant air regulations? What is the potential value added, relative to partial equilibrium approaches, of using economy-wide models in a regulatory setting?

The technical merits of using economy-wide models are the same as those identified in Section 3.1 above. These include consistency in treatment of positive and negative market effects of a regulation,[24] comprehensive coverage of all potential market effects in a way that supports identification of unintended consequences,[25] explicit recognition of finite resource endowments that explicitly factors in the opportunity costs of lost work hours or labor and capital diverted to pollution control activities, requirements that all markets clear and that increases in expenditure on one good be balanced by reductions in another.

The largest technical challenges revolve around the accurate representation of command-and-control regulations in economy-wide models and incorporating explicit structural representation of the externalities that air regulations are designed to address. For regulations that impose technology-based standards, use of some kind of engineering or PE model is an absolute necessity in order to determine the potential compliance options and cost of the regulation. These engineering analyses provide the basis for introducing a summary cost function representing the regulation into a CGE model. In this context, the PE model provides an input into the CGE analysis. Use of PE modeling output as an input to CGE modeling is particularly common in the analysis of regulations affecting transportation or electricity where relatively elaborate PE models exist and have been effectively linked to CGE models.

Complexity and data requirements are a significant challenge in economy-wide modeling. CGE modeling is most valuable when evaluating a new regulation involving an out-of-sample inference—which moves us out of the realm of historical policies. Since most academic research has dealt with questions of welfare (rather than job turnover), there is great benefit in using a very simple structural CGE model built on micro-foundations that has the flexibility to add features depending on the question at hand as time allows. However, the interpretation of results becomes more difficult as additional features are added to the model.

[24] Such as positive employment effects of required investment in pollution control equipment and negative employment effects of reduced coal use on coal mining, etc.

[25] Such as rebound or Jevons' effects associated with reduced prices for transportation fuels or lower driving cost caused by CAFE standards

PE models can be just as rigorous as GE models and often play a critical role in policy analysis. There is an art to where one should draw the boundaries between PE and GE models. If the boundaries are drawn too tightly, then key spillovers can be missed. One example involves the assessment of the land use impacts of biofuels expansion. Studies which only considered the corn ethanol-gasoline pathway overstated the impact of ethanol expansion on total cropland requirements since they ignored the by-product distiller's dried grains with solubles (DDGS), produced along with ethanol. DDGS has become an important feedstuff in the livestock sector, where it substitutes for corn in the livestock feed rations. Including this additional linkage reduces overall land use expansion by about a third (Taheripour et al., 2010). By starting out with the CGE framework, one is assured of capturing the major intersectoral linkages. Of course, if the spillover effects of a regulation apply to only a limited number of markets, it may be possible to combine them in a PE model that is more manageable than a GE model. For example, PE models that link electricity generation with electricity demand and the supply and demand of natural gas have been used extensively in analysis of air regulations.

Similarly, CGE model outputs can be used as inputs to PE models. This is particularly common in the case of household modeling using survey data. Often, rather than imbed the disaggregated households into the CGE model itself, the prices, wages and other information is fed into a simple model of household welfare allowing for determination of the differential incidence of a policy (Hertel, Keeney, Ivanic and Winters, 2007). This approach works well, provided the policy is not large enough, and the households' spending patterns are similar enough such that the pattern of aggregate spending in the economy is not significantly altered by the change in income distribution induced by the policy under consideration.

A final important advantage of CGE modeling when it comes to welfare analysis is that, provided *Walras' Law* holds. This consistency check, which is obtained by omitting one market clearing condition and checking that it nonetheless holds after the policy simulation, tells the model user that all taxes, subsidies, profits, etc. have been fully accounted for. In a multi-trillion dollar economy, analysis of a regulation involving tens of millions of dollars could easily be led astray if, for example, a change in an oligopolistic industry's excess profits was omitted. No such consistency check is available in PE analysis.

6.1.2. Criteria for choosing between models

Charge Question: What criteria could be used to choose between different economy-wide models/frameworks? What features are particularly desirable from a technical or scientific standpoint?

The models or tools chosen should line up with the problem being analyzed, both sectorally and spatially. There are potential pitfalls in geographic or sectoral aggregation that need to be addressed in each case. This is particularly true for pollutants where the spatial distribution varies, where there are complex atmospheric processes, or where sources are not distributed homogeneously.

The choice of models for a particular case can be made in a more informed way, and justified more convincingly, if models and data are publicly available in accordance with applicable information quality guidelines (OMB, 2002, 2005; U.S. EPA, 2002). It is also desirable to standardize some practices for testing the consistency of models. Here, there are some standard checks which can be applied. For example, any well-specified CGE model should be homogeneous such that (e.g.) at 10% shock to the numeraire results in a 10% rise in all prices and incomes, but no change in the optimal quantities predicted by the model. Further verification that Walras' Law (discussed in the previous section) holds in the model is a check on the internal consistency, not only of the model's theory, but also its coding and the consistency of the underlying data set. Well-specified CGE models also require explicit derivation of the behavioral equations from micro-economic foundations, peer review, thoughtful parameterization, and consistency with stylized facts. Sensitivity analysis with respect to key assumptions is also critical in evaluating models. While such models can never be fully validated, it often possible to invalidate them by showing that they fail to reproduce key historical facts (Beckman, Hertel and Tyner, 2011). This leads naturally to re-parameterization to remedy the shortcomings, and, in so-doing, one can build greater confidence in the modeling framework.

6.1.3. Interactions between costs and benefits

Charge Question: Are there potential interactions between the cost and benefit sides of the ledger (e.g. because of channels through which benefits operate) that make it difficult to make defensible comparisons between costs and benefits when social costs are estimated using a CGE framework but some or all of the benefits are estimated using a partial equilibrium framework.

Potential interactions between costs and benefits exist, but that does not invalidate the use of CGE models to estimate costs or make it impossible to design a consistent approach to both benefit and cost estimation. In technical terms, benefits and costs are said to be non-separable when changes in costs imposed on agents in the model alter the valuation of nonmarket benefits, and *vice versa*. When either costs or benefits are estimated by a method that implicitly holds the other constant, the non-separability between costs and benefits can interfere with our ability to blend those results. This is the case when CGE results on costs are compared to PE results on benefits without recognition and adjustment for potential interactions. For example, Smith and Zhao (2016) looked at EPA's calculations of the net benefits of the Clean Air Act (US EPA 2011) which used both a CGE approach and a PE approach. Smith and Zhao's calculations showed that the CGE analysis of net benefits of the Clean Air Act yielded an estimate of 0.08% of GDP, while a PE analysis yielded an estimate of 8.7% of GDP. It is important to try to reflect the interdependence of costs and benefits in some way in the model used, although much work remains to be done on representing non-separable benefits in CGE models.

Although the charge question is phrased in terms of benefits and costs, it is also useful for some purposes to focus on the distinction between market and nonmarket effects. Leaving aside issues related to incorporation of possible health effects of unemployment discussed above, costs of regulation can be broadly identified with market effects – changes in command over the goods and services for which markets exist – including the labor-leisure tradeoff. Since almost every regulation has both positive and negative market effects, it is clearer to label both as market effects and to treat their sum, which may be positive or negative, as the cost of a regulation. Likewise, the benefits typically estimated in partial equilibrium analyses of air regulations are largely based on non-market effects.

Even if non-market externalities are not estimated in a CGE model, the economy-wide approach can still yield useful information, particularly for cost-effectiveness analysis (i.e., comparing costs to achieve a given level of emission reductions or benefits). Researchers should not refuse to do part of the problem correctly because other parts are harder. Regulatory analysis is not golf; handicaps to level competition make no sense, especially because CGE estimates aren't necessarily larger or smaller than PE estimates of cost.

Section 4.5.1 above suggests a method of incorporating non-market effects for health that can be captured by including concentration levels and health care expenditures in the household optimization problem. That would allow market effects of air quality and health improvements to be determined (e.g., changes in purchases of other goods as medical expenditures fall) and for changes in marginal value of medical care as health improves due to improved air quality, etc., to be captured. This would assure that the marginal valuation of air quality improvements is based on equilibrium emissions post-regulation and including any market adjustments. Modeling a package of regulations together would also solve the co-benefits problem immediately.

It may be more straightforward to incorporate separable benefits into a CGE framework than to design the structural representation of externalities necessary to incorporate non-separable benefits. One way to do so would be to attach emission factors to the activities subject to air regulations that are represented in the CGE model, to use reduced-form air quality models to estimate changes in concentrations resulting from those emissions, and to incorporate damage functions that give the monetary valuation of changes in concentration levels. Emission factors, emission-concentration factors, and concentration-response functions exist, but not necessarily at a level of disaggregation that is consistent with the capabilities of an economy-wide model.

There are benefits of even a rudimentary effort to model non-separable benefits in a CGE framework as opposed to PE:

- Including an income constraint on willingness to pay for nonmarket benefits will avoid gross overestimates of those benefits;

- Including non-separable benefits could help close the gap between morbidity and mortality values based on lost time endowment and those based on willingness to pay;

- Deriving the value of air quality improvements from a utility function will ensure declining marginal utility from improvements in air quality;
- The equilibrium solution will thus ensure that marginal valuations of improvements are consistent with achieved emission reductions.

6.2. Imperfect Measures of Benefits

Charge Question: When benefits are included in a CGE model, it is possible that welfare measures for the economy as a whole are positive even when there is a temporary negative impact on GDP (for instance, in the Section 812 study). Relying on net measures can obscure the costs and benefits of the policy that are typically reported separately in a regulatory analysis as well as how costs and benefits are distributed throughout the economy (benefits and costs are often distributed differently). What are the potential drawbacks of using economy-wide models to present the welfare implications of compliance costs when there is not a corresponding capability to incorporate benefits?

6.2.1. Background

Changes in environmental quality, whether they are associated with the concentration of pollution in the air or in the water, have direct effects on individual well-being. They also have indirect effects on factors that contribute to individual well-being. Finally, they have additional effects through the feedback responses of other economic agents reacting to both the policies intended to improve environmental quality and the effects of those policies on prices and incomes. When prices and incomes change, we can expect resource reallocation leading to changes in environmental quality. EPA's current set of CGE models does not adequately reflect these interactions. Feedback effects are omitted.

Many of the impacts of environmental policies affect services available to people (and firms) outside markets. GDP reflects the dollar value of final goods and services produced in a domestic economy. It does not capture the effects of policy-induced changes on services that are available outside markets.

The premise implied in this question seems to suggest that general equilibrium analyses of the net benefits could lead to inappropriate judgments. This premise is misleading. The estimation of compliance costs associated with meeting specific environmental regulations, as it is explained in EPA's white papers, has always been a mixture of engineering and economic analyses. Evaluation of the GE effects of a proposed policy, as documented in these papers, necessarily requires adaptation of compliance cost measures to connect them to the specific CGE framework used for each analysis task. Even in those cases where there are detailed engineering models linked to CGE models, it is possible in principal to recover compliance costs estimates. *As a* *result, the separation of benefits and costs is not affected by adoption of a CGE framework.* What is at issue is the value of developing both *PE and CGE benefit measures* for large policy changes. The partial equilibrium cost estimates are already measured regardless of whether a PE or a CGE set of analyses is undertaken.

The ability to estimate GE cost measures depends on the design of the CGE model. For example, one could carry out a counterfactual analysis of an adopted regulation by "switching off" the change in environmental quality associated with the rule being evaluated. For example, Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) both used engineering cost estimates to modify the production structure in their model in a "with regulation" scenario and compared it with a baseline ("without regulation") scenario to develop general equilibrium measures of costs. Neither model included measures of air pollution. However, we would argue that non-separability in preferences and in some production relationships generates important feedback effects inside and outside markets. These feedbacks can affect costs by changing relative prices. As a result, for large environmental regulations that impact many sectors it may be that engineering estimates will be misleading. It is important to understand how the size of the regulation in relationship to the contributions the impacted sectors make to the overall economy affects feedbacks thru changes in relative prices of marketed goods. Research on the importance of nonseparabilities in preferences and feedbacks effects thru production relationships will be important to avoiding the perception that efforts to define a GE cost measure lead to arbitrary results.

A preferred approach would be to measure compliance costs as EPA currently does (relying on PE and engineering models) and develop CGE net benefit measures consistent with these costs. PE benefit measures would then be the discretionary element in this type of analysis.

The central point of GE research on environmental services available outside markets is that both market outcomes and nonmarket outcomes are jointly determined. Carbone and Smith (2008) have argued that social accounting matrices (SAMs) on which most CGE models are based follow the logic outlined in the "circular flow" framework. This framework omits non-market interactions with environmental systems that can create important feedbacks. As a result, it leads to model structures that overlook the feedback effects influenced through the interaction of market and nonmarket choices. The implicit decision to overlook or treat these interactions as unimportant dismisses the logic routinely used in revealed preference methods for nonmarket valuation.

Revealed preference methods (e.g., hedonic property value, travel cost, etc.) have been at the center of benefit measurement in environmental economics for over 50 years. All of them must assume the tradeoffs that motive choices arise from relationships between market goods and services (including a person's leisure time) and nonmarket services. As a result, these tradeoffs must be influenced by the composite of market services and goods and nonmarket services. This joint influence implies that the nonmarket market services must be entered in a non-separable way to the functions used to define those trade-offs.

The importance of this criticism depends on both the importance of these non-separabilities and the character of the policy being evaluated. One must ask: How does the policy affect different sectors in the economy? And, how do the services arising from those sectors influence people? EPA's current yardstick for judging whether a general equilibrium analysis is needed involves comparing the aggregate compliance costs associated with a proposed rule, on an annual basis, to gross domestic product. This comparison is inappropriate. The analysis must consider the importance of compliance costs for the sectors that will be affected as well as the interconnections of the affected sectors with the rest of the economy. Regulated entities rarely comply with regulations as discrete, separable directives. Rather, they have to comply with multiple strands of regulatory requirements from the same and different regulatory offices and agencies. The effect of regulation generally is further complicated by uncertainties related to technological and permitting conflicts. It is not unusual, for example, for Regulation A to prescribe Technology 1 (or for Technology 1 to be the least-cost method of compliance with Regulation A), and Regulation B to prescribe Technology 2 (or for Technology 2 to be the least-cost method of compliance with Regulation B), where Technologies 1 and 2 are incompatible. As a result the engineering cost analysis reflects assumptions that are best interpreted as incorporating compromises in how these inconsistencies are treated. The literature has not addressed how to incorporate these technical, engineering assessments into CGE models. Matus et al. (2008) is one example discussing the issues.

Similar interconnections arise on the household side and also cause GDP to be a poor measure of welfare. Kahn and Zheng (2016) provide an excellent example of how individuals can undertake averting actions to reduce their exposure to air pollution. These actions can have unintended effects – e.g., contributing to everyone else's air pollution and congestion, altering gasoline use, and changing individual time locations. Here is their description:

> Today is a typical winter Monday in Beijing; the temperature in the morning is always below freezing. Siqi wakes up very early takes a look at the air pollution monitor application on her iPhone, which reports two versions of the city's air pollution index: one from the US Embassy in Beijing, and the other from China's Ministry of Environmental Protection (MEP). It will be a terrible day again: US Embassy index reports a "hazardous" day and the MEP reports that the air is "highly polluted".
>
> Like other successful Beijing urbanites Siqi has several protection strategies to reduce her exposure to pollution. She owns a car, and on days with heavy pollution she drives to work rather than riding her bike. There are many products on the market to protect people from air pollution; and air purifier costs US $490 and an air mask cost ninety cents. Each mask, which researchers believe reduces one's exposure to pollution by 33 percent, is effective for 10 days.

> Wearing a mask isn't glamorous, but exposure to thirty minutes of outdoor air on a hazy day in Beijing causes a sore throat. On highly polluted days, most people walking or riding bicycles wear masks, and Beijing's supermarkets, pharmacies, and shops are often sold out of them – especially the high quality 3M Particulate N95 masks, which are 88.5 percent effective in reducing exposure to the smaller PM 2.5 particles.
>
> Siqi decides to drive her car today to protect herself from the polluted air. Her commute to Tsinghua University can take either twenty minutes by bicycle or ten minutes by car without traffic. During peak hours the trip can the trip by car takes thirty minutes and in very bad traffic you can take an hour. To avoid traffic she often gets to her office before 7 a.m. Thanks to the flexible working hours that professors enjoy, she can adjust her commute time to avoid traffic but many of her friends aren't that lucky. (pp. 10-11)

To date, there have been limited analyses of the implications of general equilibrium effects for benefit measures associated with environmental regulations. The literature that is available suggests that even small changes in these costs as a fraction of aggregate income can cause large discrepancies between PE and GE welfare measures. The extent of the difference appears to depend on the magnitude and distribution of the compliance costs across sectors [see Carbone and Smith (2008) and US EPA (2011), Chapter 8].

6.2.2. Absolute measures or relative comparisons

Charge Question: Given the many assumptions and uncertainties inherent in modeling the impacts of a regulation in a CGE or other type of economy-wide framework, are absolute measures of welfare, social costs, and benefits more scientifically defensible or should the focus be on relative comparisons across proposed regulatory alternatives? (Should we have greater confidence in the estimated welfare change between baseline and policy scenario or in the relative difference in welfare across policy scenarios?)

A comparison of the net benefit measures in relative terms (i.e. compared to one baseline scenario) is an interesting proposal. However, it is not especially informative without the companion relative analysis of the PE net benefits using *the same reference* scenario. Under these circumstances, a relative comparison might offer a gauge of the importance of the interaction of GE with the specific features that define each scenario.

In our judgment it is not possible to evaluate, given the extent of the literature available, the merits of reporting findings in terms of the relative changes versus the presenting the welfare changes in levels. It would seem more important to compare the welfare changes attributed to policies to the associated changes in other measures of economic activity that would be observable ex post. Relying on relative measures would not be consistent with this approach.

Confidence in GE estimates only would be justified if there is a systematic assessment of a set of observable ancillary changes in economic activity that can be estimated and documented. For example, if the logic associated with estimating the benefits from an improvement in air quality implies that individuals will spend more leisure time in outdoor activities, then it is important to evaluate whether the CGE models used to develop the welfare assessment can also predict these types of changes in response to the changes in air quality. If not, what would it take to include these types of ancillary activities in the models?

One might also ask whether it is possible to use both PE and GE models to "back cast" the outcomes of the policy in terms of these ancillary activities and expenditures as a means to increase confidence in the welfare assessment derived ex ante from the model.

6.2.3. General v. partial equilibrium to assess net benefits

Charge Question: What are the technical merits and limitations to presenting both general equilibrium and partial equilibrium measures when assessing the net benefits of a regulation?

There are clear advantages to presenting both PE and GE measures. There are two primary limitations. The first arises from the need for a framework that describes the features of the policy that might give rise to differences between these two measures of benefits and costs. As the EPA White Papers document, such a framework has not been developed and evaluated in the published literature.

The second stems from a parallel need to characterize the ways in which the services provided by environmental resources enter the models used for the GE and PE analyses. This assessment must consider specifically the implied market and nonmarket interactions and their implications for the model's characterization of feedbacks in its general equilibrium solution.

6.3. Presenting Results

Charge Question: EPA guidance states, "To promote the transparency with which decisions are made, EPA prefers using nonproprietary models when available. However, the Agency acknowledges there will be times when the use of proprietary models provides the most reliable and best-accepted characterization of a system. When a proprietary model is used, its use should be accompanied by comprehensive, publicly available documentation." If the SAB advises that the use of economy- wide models may be technically appropriate in certain circumstances, are there particularly useful ways in which results from a CGE model could be presented to the public and policy makers?

6.3.1. Information to include

Charge Question: What information would be most useful to include when describing a CGE-based analysis of an air regulation to make it transparent to an outside reader in *a way that allows for active engagement of the public in the rulemaking process (e.g., regarding model scenarios, criteria used to inform model choice, nature of any linkages between economy-wide models and other modeling frameworks, parameter choices)?*

There are two issues that need to be addressed. The first is with respect to the use of proprietary models. To be clear, we assume that proprietary models are those meeting the definition set forth by the NRC Committee on Models in the Regulatory Decision Process (NRC 2007) which defines a model as "proprietary" if any component of the model is not available for free to the general public. Overall, we do not think proprietary models should be used, if at all possible. It is highly unlikely that the sacrifice in transparency, including the inability for qualified third parties to reproduce results, be worth the additional gain in the characterization of a system. EPA should make all PE and CGE models (including data and computer code) available to the public to encourage outside validation.

The second issue is how to make economy-wide modeling transparent to non-modelers, including EPA officials. Whether discussing engineering, PE or economy-wide models, the same transparency standards should apply. The ultimate goal in describing the model is to provide outside readers the information necessary to both understand and reproduce the results. With this in mind, it is important to develop models that are as simple as possible, and in the case of economy wide models, to make data, structure and code publicly available. Due to the complicated nature of CGE-type models, EPA might consider providing a table of relevant parameters used in the model (e.g., elasticities, initial prices, and so on) indicating which were taken from the literature, and which were calibrated specifically for the model, and describing quantitatively their imprecision. A diagram or flow chart could be used to indicate the feedback loops that are assumed in the model. Both the table and flow chart may also be used to clarify how sensitivity analysis was conducted.

It is critical to provide a clearly written explanation of what a given CGE-type model can and cannot do. Cogent descriptions are essential for showing how the model was estimated, emphasizing the key channels within the model that are driving the results, as well as how the results should be interpreted.

A public vetting of the models may be helpful for aiding public understanding and engaging qualified third parties in model validation. This also provides a forum for comparing and contrasting results of competing models, In general, it can be valuable to present sensitivity analyses or results of alternative models, together with notes on what differences among their assumptions, inputs or approaches seem to be responsible for any differences in outcome. Such sensitivity, or in some cases, lack of sensitivity, can help a reader less familiar with the approaches to understand the implications of results and their limitations for policy decisions.

Another possibility is for EPA to develop a simple economy-wide model (perhaps along the lines of the "DICE" model) that it could make available to the public that would allow outside parties to manipulate model parameters and assumptions within a given policy framework.

6.4. Uncertainty and Economy-Wide Modeling

Charge Question: The National Academy of Sciences (2013) identifies three type of uncertainty: statistical variability and heterogeneity (or exogenous uncertainty); model and parameter uncertainty, and deep uncertainty. Are certain types of uncertainty more of a concern when evaluating social costs, benefits, or economic impacts in an economy-wide framework? Are challenges or limitations related to these uncertainties more of a concern than for partial equilibrium approaches to estimation?

In general, uncertainty is always a concern and should be addressed in any analysis. This is not specific to economy-wide frameworks, but to all types of models and quantitative analyses. When uncertainty is neglected and only point values from a quantitative analysis are presented, it can mislead the reader to assume that even the experts have more confidence in those estimates than is the case.

Moreover, there is a well-known result called Jensen's Inequality in mathematics, and the "Flaw of Averages" in more recent literature (Savage, 2009), that states that the expected value of a function of a random variable is, in most cases, not the same as the value from the function applied to the mean of the random variable. In other words, the result of a model using average or "best-guess' values for all parameters will not be an appropriate measure of the expected value of the model result that accounts for the full distribution of uncertainty in all parameters. This is equally true for general equilibrium and partial equilibrium models.

The Institute of Medicine (2013) hierarchy of uncertainty is one of many possible ways to distinguish different types of uncertainty; another popular typology is provided by Morgan and Henrion (1990). All types of uncertainty are a concern, in the sense that they should be acknowledged and addressed when possible. Where they differ is in the availability of formal rigorous quantitative techniques for treating them.

Parametric uncertainty is the most straightforward to address. The formal quantitative methods include systematic sensitivity analysis (Saltelli et al., 2008), uncertainty propagation via Monte Carlo simulation (Kroese et al., 2011), and the delta method (Jorgenson et al., 2013). In each case, the model includes a parameter whose value is either not known with certainty or is an inherently variable quantity (e.g., commodity price or precipitation). Sensitivity analysis consists of altering the values for the parameter(s) of interest and reporting the corresponding changes in model outcome. Monte Carlo simulation requires the assumption of probability distributions or specification of a stochastic process to describe the possible values for the parameters(s), drawing random, independent and identically distributed samples, and characterizing the frequency distribution and other measures of the resulting set of model outcomes. The delta method, which is often used in econometric software, uses a first-order Taylor Series approximation to a model to map covariance matrices of parameters into covariance matrices for the model's endogenous variables. These methods are appropriate for estimating the impacts of both statistical variability and of parameter uncertainty, but they do not address uncertainties related to underlying data, such as measurement error– a key form of uncertainty that is routinely ignored.

Model uncertainty is much more difficult to treat in a formal quantitative fashion. Unlike an uncertain model parameter for which there exists a true numerical value, albeit unknown, there is no unambiguous way to specify all possible models that could exist and their relative likelihood. Nevertheless, model uncertainty is a source of concern. When specific questions of model resolution or the inclusion of a specific process are raised, sensitivity analysis can be used to shed light on whether the impacts of model structure are large.

Deep uncertainty, not knowing what we don't know, is always present, and all analysts should be vigilant and aware of human limitations. However, there is no formal accepted method for addressing this source of uncertainty. Deep uncertainty is potentially present in all forms of analysis, and is not unique to general equilibrium modeling.

6.4.1. Best practices

Charge Question: How can these types of uncertainty be addressed in an economy-wide modeling framework? Are there best practices to ensure that can EPA be reasonably confident that it is producing credible welfare or economic impact estimates (e.g., model validation exercises)?

The preferred formal methods for addressing statistical variability and parameter uncertainty are discussed above, and consist of sensitivity analysis, uncertainty propagation via Monte Carlo simulation, and the delta method. These methods are well-developed and are part of the set of best practices for all numerical computation, not only economy-wide modeling. Addressing these forms of uncertainty does require assumptions about the probability distribution(s) of the underlying parameter(s) and any exercise in sensitivity analysis or Monte Carlo simulations should make clear the state of knowledge about those underlying distributions.

Model or structural uncertainty and deep uncertainty do not have any formal quantitative best practices to address them. These sources of uncertainty are also common to all computational modeling. The primary accepted best practices are the awareness by modeler or analyst of human limitations when it comes to judgment of uncertainty.

6.4.2. Sensitivity analyses

Charge Question: Are sensitivity analyses of important model parameters and/or model assumptions a technically appropriate way to assess uncertainties involved in this type of economic modeling? Are there circumstances in which the use of multiple models should be considered?

As described above, sensitivity analyses are one of the standard approaches for addressing variability and parametric uncertainty. It is certainly one appropriate method of exploring the impacts of these sources of uncertainty. In addition, sensitivity analysis can be used to compare alternative model formulations. However, this is primarily useful for comparing alternative variations in the same model (e.g., change in spatial/temporal resolution, inclusion of a specific process), less so for comparing different models.

A sensitivity analysis in the CGE tradition perturbs parameters of the model, which is an enterprise that describes the kind of uncertainty automatically captured by standard errors and covariances of estimated parameters in the econometrics tradition. A sensitivity analysis in the econometric tradition perturbs the model by adding new variables or omitting existing ones. This sort of sensitivity analysis can also be done in the CGE tradition. It would be an interesting experiment to have several econometricians independently study a problem to see how similar their conclusions are, and likewise with several CGE modelers. This has been the practice in the Stanford Energy Modeling Forum, and might be tried at EPA.

Comparisons among different models must be made with great caution. In general, the range of outcomes from different models of the same type greatly understates the true range of uncertainty. Social pressures to not deviate "too far" from other published models can lead to unintentional calibrating of key outcomes. This phenomenon is also common across all computational modeling communities, and is not unique to CGE models. The best practice, given sufficient funding support and time, is to perform a Monte Carlo simulation on all models of the same type, using the same underlying probability distributions for parameters. The resulting distribution of model outcomes would integrate both the parametric uncertainty and a subset of model uncertainty as represented by the models included.

6.4.3. Precision

Charge Question: Are CGE models precise enough to accurately represent the general equilibrium welfare effects of a regulation that has relatively small engineering costs or monetized benefits? What about for evaluating economic impacts? If yes, under what circumstances?

Most CGE models are solved using either a non-linear optimization algorithm or a technique called Mixed Complementarity (Rutherford, 1995). These routines are typically iterative and refine solutions until the differences between the left and right hand sides of key equations in the model (or a summary measure such as the sum of squared differences) falls below a specified convergence tolerance. By design, the convergence tolerances in most CGE models are several orders of magnitude smaller than the main effects being computed for relatively large policy experiments, and are therefore are not an issue. However, for policies causing extremely small price or quantity effects (i.e., for changes in industry prices or output that are very small in percentage terms), convergence tolerances may be relevant. However, a simple test for this problem would be to examine whether the model's prediction for a policy outcome of interest varies significantly with a tightening or loosening of the convergence tolerance. If it does, and such small regulatory or policy changes are one-offs, CGE modeling is inappropriate and no further analysis would be cost-effective. If, however, an agency is carrying out a large policy change by means of a series of small regulatory changes, an appropriate analytical strategy would be to combine the small steps into a representation of the entire regulatory sequence and model that broad policy on an economy-wide basis.

6.4.4. Characterizing degree of uncertainty

Charge Question: How can the overall degree of uncertainty be characterized when reporting results from economy-wide models?

A critical distinction needs to be made with regard to the results of an uncertainty analysis. No uncertainty analysis, for any type of computational model, can realistically claim to be the "true" objective measure of uncertainty. The reasons for this are that we do not know the "true" probability distributions for model parameters, nor do we have an objective specification of all possible model structures that could be constructed and a universally accepted measure of their relative likelihood. Finally, the inevitable existence of deep uncertainty means that any characterization of the other forms of uncertainty could be too narrow.

The value of an uncertainty analysis is more nuanced. Any uncertainty analysis is a "What if…" exercise that elaborates on the implications of different plausible assumptions. One valuable use of a characterization of uncertainty is in choosing among alternative decisions. Whether a regulation, a business strategy, or an engineering design, we want the decision to be robust with respect to uncertainty. A decision is robust if substantially different data or model specifications have no effect on the preferred decision, and especially if these alternatives are controversial.

A second value of an uncertainty analysis is it can identify areas in which the value of new information or methods is large with respect to the decision at hand. It may be that changes in certain parameters have little impact on key modeling outcomes while changes in other parameters can lead to significant changes in key modeling outcomes. Armed with estimates of the value of information, EPA can focus resources on generating the data or new methods required.

With the above objective in mind, the overall degree of uncertainty from a computational model can be characterized by providing a set of percentiles for each uncertain outcome of the model. For example, results can be summarized by reporting the 5th, 25th, 50th, 75th, and 95th percentiles for each outcome. Because most uncertain outcomes will not have a normal distribution, reporting the mean and standard deviation are not sufficient to communicate the results of uncertainty propagation. In the case of sensitivity analysis, upper and lower bounds should be reported for each outcome of interest.

6.5. Priorities for Future Research

> *Charge Question: Bearing in mind current and future resource limitations, what should EPA prioritize as its longer term research goals with respect to improving the capabilities of economy-wide models to evaluate social costs, benefits, and/or economic impacts?*

In this section we summarize and prioritize recommendations made elsewhere in the document. In doing so we use the timing nomenclature introduced in the introduction. Actions that are *possible now* can reasonably be done very soon—roughly now through the next five years; those described as *near term* require more time—roughly what could be developed, peer-reviewed and suitable for regulatory use in five to ten years; and those described as *long term* would require ten years or more to be developed and thoroughly vetted. However, because EPA should carry out some of these actions concurrently, we list them in order of priority rather by timing horizon.

For wider use of economy-wide models to evaluate air regulations, EPA's top priority should be to encourage further development of CGE models that can capture involuntary unemployment. The existing literature in the area is both small and recent, so it is not possible now to capture these effects in routine regulatory analysis. However, employment-related transition costs can contribute to the social cost of a regulation (see section 3.3) and they are very important for evaluating economic impacts (see sections 5.1, 5.3, 5.4, and 5.5) so moving the literature in that direction is essential. In the near term the focus should be on frictional unemployment but that should be regarded as a first step in a longer research agenda that would eventually include structural unemployment.

EPA's second priority should be to encourage far more inclusion of non-market benefits into economy-wide models. As discussed throughout the report, and in section 4 in particular, benefits are captured less well in CGE models than costs. In large part the difference is due to the availability of data: much work has been done estimating non-market benefits in particular locations and situations but there are not the kind of comprehensive national-level datasets that are available for modeling costs. Work on improving the treatment of benefits should begin immediately. It should be expected that some improvements will be possible in the near term but, particularly due to data limitations, the research will need to continue over the long term. As noted throughout the discussion of benefits in the report, a particularly important aspect of this research agenda should be to move away from the currently conventional practice of imposing separability between non-market benefits and goods and services that are involved in market decisions.

A third priority should be for EPA to encourage model developers to introduce explicit treatment of mortality risk into the utility functions used to represent households. As discussed in section 4.2, this is necessary to reconcile economy-wide measures of equivalent variation with partial equilibrium measures of the willingness to pay for risk reductions (that is, with the VSL). Better modeling of risk (and risk perceptions) is a near term priority. However, initial progress is possible now by relatively simple approaches such as moving toward an expected utility framework.

Priority four should be for the EPA to encourage research on linking relatively aggregate economy-wide models to more detailed models of households, industries or regions. As noted throughout the report, there will always be tension between the degree of detail in the datasets available for parameterizing economy-wide models (which is relatively low) and the degree of detail desirable for understanding the costs, benefits, and impacts of any given air regulation (which is often relatively high). As a result, it will often be very useful to use linked models: (1) an economy-wide model to impose budget constraints, capture flows of goods and services between sectors, model long term supplies of primary factors, and calculate broad welfare impacts; and (2) a more detailed model of a particular sector (say electricity), or of a region (for example, tracking air emissions from sources to exposed populations), or of households by income and demographic characteristic (understanding regressivity, for example, or the impact of cross-regional ownership of financial assets). The focus on this work should not be on linking per se (on which there is a long literature in energy modeling and elsewhere) but rather on understanding the inconsistencies that arise from linked rather than fully integrated models. Research on linking should be a near term priority.

A fifth priority would be for EPA to convene a series of model comparison exercises for models of air regulations like those carried out under the auspices of the Stanford Energy Modeling Forum (EMF) for energy models. One analysis that would be possible now would be a comparison of open economy and global models for estimating the impacts of U.S. regulations on the U.S. As discussed in the report, open economy models focus primarily on the U.S. and use sets of aggregate rest-of-the-world equations to represent supplies of imports and demands for exports. Global models, in contrast, include full models of regions outside the U.S. Global models allow more detailed analysis of the impacts of policies on trade patterns and international capital flows, but they are more complex and can be less transparent. An important research question would be to identify when each type of model is most appropriate.

A second model comparison exercise that would be possible now is an assessment of the importance of fiscal and trade deficit closure rules. It is well established in the literature that both are important for understanding the GDP and welfare impacts of a regulation but it is less clear how those assumptions interact with other structural features of CGE models. In addition, EPA's long term regulatory analysis should move toward a standard treatment of both deficits to avoid having different studies of a single regulation come to different conclusions because of different assumptions about the fiscal or trade closure.

Priority six should be to encourage research on the impact of heterogeneity within regulated industries. For example, emissions intensities can vary considerably across plants and firms within an industry but economy-wide models typically use a single representative firm to characterize a sector. In addition, some regulated industries have relatively few firms but they are typically represented in economy-wide models as perfectly competitive. Perfect competition may be a reasonable assumption in the long run but oligopoly behavior may influence transition costs in the short to medium run. More work in this area would be valuable and it should be a long term priority.

Finally, the seventh priority should be for EPA to help establish and open-source project to assemble a freely-available database for use in CGE modeling. Access to detailed, high quality data, especially time-series data, is a considerable barrier to the development of CGE models. In addition, as discussed in several places in the report, regulatory requirements for data quality are stringent and would be easier to meet with well-documented, publicly-available data sources. Building such datasets is resource-intensive and time-consuming to do well so this should be regarded as a long term priority. Moreover, an ongoing challenge is likely to be a version of the public goods problem: the professional payoff to academic researchers from building datasets may be lower than that from using the datasets.

7. GLOSSARY OF TERMS

Accuracy: In general, the accuracy of a result from a model is the degree to which that result approximates the "true" but unknown value. In a regulatory analysis, the results of most importance are deviations between a business-as-usual baseline economy and an alternate economy with the regulatory change imposed. That is, if Y is a variable of interest and a model reports that it will be equal to Y_1 in the baseline and Y_2 under the regulation, the result of most interest is the deviation $\Delta Y = Y_2 - Y_1$. The accuracy of the individual values of Y and the accuracy of ΔY may differ. For example, if the true relationship between Y and a policy variable X is $Y = \beta X$ but a model incorrectly represents it as $Y = \beta X + \gamma$, both Y_1 and Y_2 are inaccurate: they will be biased by γ. However, ΔY will be $\beta \Delta X$ and is unbiased. Throughout this document, unless otherwise indicated references to the accuracy of a model will mean the accuracy of its reported policy deviations ΔY.

Benefits:

Compliance costs:

Computational general equilibrium model:

Economy-wide model:

Equivalent variation:

Exact aggregation:

Full income:

General equilibrium:

Hard linkage:

Partial equilibrium:

Precision: The precision of data, assumptions or model results is its inherent degree of uncertainty. It is often characterized as a confidence interval (if statistical) or as the number of significant digits (otherwise). Precision is limited by four broad factors: a) uncertainty in the parameters of a model (i.e., the covariance matrix of the parameter estimates); b) uncertainty in the measurement of data (e.g., due to measurement error or aggregation); c) the residual variance from estimating equations; and d) finite precision in the calculation and storage of data by computers. Throughout this document, precision will be used to refer to the individual or combined impact of these factors relative to the magnitude of the quantity of interest. Higher precision means (for statistical quantities) tighter confidence intervals relative to the magnitude of a variable (e.g., a smaller coefficient of variation), or alternatively, to a larger number of valid significant digits.

Representative agent:

Reproducibility: Information is "reproducible" when it is capable of being recreated by a qualified third party based on only the instructions disclosed, The concept of reproducibility applies to all forms of information, including data, assumptions, models and results. Results are capable of being substantially reproduced if independent analysis of the original or supporting data using identical methods would generate similar analytic results, subject to an acceptable degree of imprecision or error. The degree of tolerable imprecision or error depends on the scale and scope of how the information would be used.

Risk:

Social costs:

Soft linkage:

Transition costs:

Separability:

Value of a statistical life:

Willingness to pay:

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