UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON D.C. 20460

OFFICE OF THE ADMINISTRATOR
EPA SCIENCE ADVISORY BOARD

September 29, 2017

EPA-SAB-17-012

The Honorable E. Scott Pruitt
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Subject: SAB Advice on the Use of Economy-Wide Models in Evaluating the Social Costs, Benefits, and Economic Impacts of Air Regulations

Dear Administrator Pruitt:

The EPA's National Center for Environmental Economics (NCEE) requested advice from the Science Advisory Board (SAB) on the use of economy-wide modeling for assessing the benefits, social costs, and economic impact of air regulations. NCEE asked the SAB to: (1) evaluate the technical merits, methodological challenges, and potential value of using economy-wide models as a supplement to the EPA's existing analytical tools; and (2) to suggest paths forward that would improve the usefulness of economy-wide models for regulatory analysis. In response, the SAB convened an advisory panel on Economy-Wide Modeling of the Benefits and Costs of Environmental Regulation. The enclosed report provides the SAB's resulting assessment and recommendations.

The economy-wide modeling approach that would be most useful for regulatory analysis is computable general equilibrium (CGE) modeling. CGE models divide the overall economy into a detailed set of economic agents who interact through markets. Some agents are producing sectors, such as motor vehicle manufacturing or retail; some are household groups, such as single-parent families in the Southeast; and some are governments. Each agent is, ideally, represented by a validated behavioral model, including relevant constraints on its budget. The agents interact through markets for goods, services, labor and capital. These models are described as *general equilibrium* because they simultaneously solve for all outcomes in all markets. For example, in a general equilibrium model the outcome in the motor vehicle market is consistent with the outcome in the labor market, and the outcomes in both markets are consistent with tax rates and government spending.

The SAB finds that CGE models could provide several important benefits as a supplement to the EPA's current set of analytical tools for the analysis of air regulations:

- By imposing budget constraints on all agents, CGE models are capable of providing a fiscally disciplined, consistent and comprehensive accounting framework. They can ensure that projected behavior of firms and households in a regulated market is fully consistent with the behavior of those agents in other markets. If income has not changed, for example, then greater spending in one market must lead to lower spending elsewhere, reduced saving, or both.

- Consistent representation of behavior, in turn, leads to connections between markets, allowing CGE models to pick up effects that spill over from one market to another. Changes in the demand for vehicles, for example, may lead to changes in the demand for gasoline and public transit, just as they also may change demands for inputs such as fabricated metals and, in turn, the output of the mining sector. International connections may also be important as domestic policies may influence imports, exports, or international flows of capital. These connections between markets are especially important for labor and capital. Policies that have impacts on household saving, for example, will lead to changes in investment and capital formation, which in turn affects the social cost of the policy.

- CGE models are capable of accounting for the interaction between regulations and other policies, such as existing or contemplated tax rates. A regulation added on top of the existing tax system may exacerbate or ameliorate existing sources of economic inefficiency. An extensive literature has shown that these interactions can have a very significant impact on the social cost of the regulation.

- CGE models may contribute to the transparency of an analysis by explicitly stating all assumptions about the behavior of producers and households.

In practice, however, CGE modeling will be challenging to adopt for analysis of many air regulations. The SAB identifies the following barriers:

- CGE modeling imposes formidable data requirements. Since the approach is comprehensive, it requires consistent, high-quality data on all agents in the economy. Moreover, such data may need to be available for a long historical period if the analysis is to support statistical determination of key parameters describing the behavior of the agents.

- Air regulations often fall on narrow segments of the economy: specific industries, production processes, or locations. However, long-term, comprehensive data available from public sources are often much more aggregated and may not allow the agency to isolate the firms or households directly affected by a regulation from those that are not affected. As a result, it can be difficult to map the detail of a proposed regulation into a set of appropriate inputs for a CGE model. In many cases, it will be necessary for the EPA to link relatively aggregate CGE models to more detailed models of particular sectors, household groups, or regions.

- Some consequences of regulations are not included in most CGE models. An important example is unemployment. To date, most CGE models have been designed and used for medium to long-run analysis—a period long enough to allow labor markets to return to a full-employment equilibrium. The literature on models with short-term labor market transition costs (including, but not limited to, unemployment) is both small and still emerging. In addition, more work is needed on modeling longer-term structural unemployment, especially at the regional level. Time and resources will be required to improve the ability of CGE models to capture these impacts.

- Some CGE models may fail to contribute to transparency. Highly detailed models are complex, and the mechanisms driving their results can be opaque, especially to outside observers. The use of CGE models for regulatory purposes will need to be accompanied by significant efforts to make the key drivers behind modeling results clear for both policymakers and the public. Appropriate sensitivity analyses and the quantification of modeling uncertainties will also be essential and should be a key part of any regulatory analysis.

In addition, although CGE models can be broadly suitable for the analysis of social costs, they have not achieved their potential for analysis of the benefits of air regulations. Key barriers include:

- Most CGE models do not include an explicit treatment of the links between mortality and morbidity risks, budget constraints, and behavior. Typically, CGE analysis has measured the impact of changes in mortality and morbidity through changes in the size of the effective labor force. However, the broader research literature indicates that individuals have a significant willingness to pay (WTP) for reductions in mortality risk. Integrating explicit preferences about mortality risk into CGE models would be a very important step. It would improve the EPA's traditional methodology by ensuring that implied behavior is consistent with budget constraints, and it would improve CGE analysis by capturing the impacts of risk reductions on other agent behavior.

- The benefits of a cleaner environment beyond the changes in the labor force noted above are not included, or are not modeled well, in most CGE analyses. An extensive and long-standing literature has shown that individuals derive significant value from environmental quality. Integrating these benefits, technically known as "use values" for environmental quality, into CGE models would significantly improve their usefulness for analysis of air regulations.

To overcome these barriers and to realize the potential benefits that CGE models could contribute as part of the EPA's analytical approach, the SAB recommends that the EPA take the following actions:

- Initiate and support a third-party open-source program to assemble and maintain publicly available high-quality datasets for use in CGE modeling. Doing so would address the single greatest obstacle to the development of high-quality CGE models for regulatory analysis. Moreover, such a database is an example of a public service that is unlikely to be provided by actors in the private sector alone, yet will benefit public and private decision makers alike, and will greatly facilitate communication around the potential impacts of air regulations. State governments would be key potential beneficiaries of this program.

- Support improved modeling of labor market impacts in the short and medium run. Such analysis would allow CGE models to do a better job of evaluating both the social costs and the economic impacts of regulations.

- Support more extensive modeling of the benefits of improvements in air quality, including both explicit modeling of risk aversion, and modeling of the interaction between environmental quality and household demands for market goods.

- Support research identifying and quantifying the inconsistencies that arise when an aggregate CGE model is linked to a detailed sectoral model. As noted above, this kind of linkage will be a frequent need in the analysis of air regulations. A substantial literature exists on how models can be linked, but more work is needed to determine whether the necessary approximations create large or small inconsistencies in the analysis.

Finally, two important caveats should be noted about CGE models. First, they are designed for evaluating how a policy will change the economy relative to a specified baseline, not for forecasting the baseline itself. What actually happens when a regulation is adopted will usually differ from prior modeling results due to unrelated events, such as business cycles or unexpected innovations, that move the economy away from the baseline. Thus, CGE models should not be regarded as short-run forecasting models, and the same characteristic makes them difficult to validate against historical data. Second, CGE models rely heavily on assumptions about the structure of the objective functions and constraints used to model the behavior of households and firms. Because relatively few observations of economy-wide historical data are available, it can be challenging to obtain precise statistical estimates of some parameters in a model, and it will also often be the case that several alternative models of a given agent’s behavior could be equally consistent with the historical record. Thus, there may be ambiguity about the most appropriate specification to use. In light of these caveats, it will be very important to carry out sensitivity analysis with respect to both baseline assumptions and key structural assumptions.

Over its history, the EPA has been a leader in the development and use of benefit-cost analysis. Although the challenges noted above are formidable, the SAB recommends that the EPA continue that leadership by beginning to integrate economy-wide modeling, and computable general equilibrium modeling in particular, into regulatory analysis in order to offer a more comprehensive assessment of the benefits and costs of air regulations. The SAB appreciates the opportunity to provide advice on the subject and looks forward to receiving the agency's response.

Sincerely,

/s/ /s/

Dr. Peter S. Thorne, Chair
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Dr. Peter J. Wilcoxen, Chair
SAB Economy-Wide Modeling
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Enclosure

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Acronyms and Abbreviations

CGE	Computational General Equilibrium
CV	Compensating Variation
DSGE	Dynamic Stochastic General Equilibrium
DWL	Deadweight Loss
ECA	Engineering Cost Assessment
EWM	Economy-Wide Model or Modeling
EV	Equivalent Variation
GE	General Equilibrium
GHG	Greenhouse Gas
IO	Input-Output
MAC	Marginal Abatement Costs
NAAQS	National Ambient Air Quality Standard
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 (NCEE) in the EPA Office of Policy requested advice from the Science Advisory Board (SAB) on the use of economy-wide modeling (EWM) for assessing the benefits and costs of air regulations. The agency's current approach starts with detailed engineering cost assessments (ECAs) that evaluate technical options for compliance in order to produce the expected direct cost of the rules to regulated firms. EPA then uses those costs in partial equilibrium (PE) market models to estimate social costs, which include a broader range of impacts. The agency also uses PE models to evaluate benefits. EPA asked the SAB to: (1) evaluate the technical merits, methodological challenges, and potential value of using EWMs as a supplement to these tools; and (2) to suggest pathways forward that would improve the usefulness of EWMs for regulatory analysis. In response to the EPA's request, the SAB convened the Economy-Wide Modeling Advisory Panel. 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).

Several types of EWMs have appeared in the literature, including: input-output (IO) models, macroeconometric models, hybrid IO-macroeconometric models, general equilibrium (GE) models, and dynamic-stochastic general equilibrium (DSGE) models. The most suitable approach for measuring social costs, and the one that has been used most extensively in the literature for environmental policy analysis, is GE modeling. Other methods should not be used for evaluating social cost but may be suitable for evaluating certain regulatory impacts in particular circumstances.

Pure GE models have two distinctive characteristics: (1) they solve for 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 will 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 are adequate data available to build one. Moreover, a model with that level of detail would be opaque to outside observers, which would be a significant liability in conveying the analysis to the public in a clear and convincing way. As a result, a consistent theme in our guidance below is that it will often be necessary and appropriate for EPA to link a GE model having a modest degree of detail to one or more PE models having greater detail. Linked models will usually involve some degree of inconsistency in the definitions of overlapping variables and parameters, but that may be acceptable given the increased degree of detail that a linked analysis could provide.

The SAB suggests the following additional points as guidance for EPA with respect to GE modeling of air regulations.[1] First, we strongly agree with the agency that GE modeling should be considered only as a supplement to the agency's current practices, not as a replacement. In general, air regulations cannot be evaluated in a GE model without essential data provided by an engineering cost analysis. Moreover, GE models that are currently available, or that will be available in the near future, are not capable of providing all of the analytical results needed by the agency: PE analysis are needed in many instances.

Second, we recommend that EPA emphasize transparency in its use of GE models. These are complex tools and they are potentially opaque. Transparency can be enhanced by making the model code, input data, and parameter choices public, and by presenting the information in a manner that facilitates reproducibility by outside users. Providing this information reduces the likelihood of unnecessary and potentially costly misperceptions about how the models work, and about how each analysis was done. Information quality standards apply to data and analyses disseminated by the agency, and the agency can rely on data supplied and analyses performed by other entities (whether public, nonprofit or private) only if they meet the same standards.

Third, the following criteria should be used when evaluating the suitability of a given CGE model for use in evaluating air regulations, whether it is used for calculating social costs, benefits, or economic impacts: (1) availability, completeness, and transparency of data and 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 several essential theoretical properties 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. As with information quality standards, these criteria apply to models used by EPA, as well as models used by other entities (whether public, nonprofit or private) if they want EPA to be able to use them.

Fourth, treatment of uncertainty, and recognition of sources of uncertainty, is critical for ensuring the credibility of the agency's analytical GE analysis. Uncertainty arises from several sources, including: uncertainty in the data inputs used in the model; uncertainty arising from the statistical estimation of parameters used in the model; uncertainty due to aggregation; and uncertainty arising from ambiguity about the appropriate form of the model's behavioral equations. A frank portrayal of uncertainty associated with an analysis will help to avoid giving a false sense of precision in reporting results, and it will also help guide future research priorities. To be clear, the need to characterize uncertainty transparently arises under all analytical approaches, including PE analysis; however, the scale and complexity of GE models makes the task more challenging.

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[1] Although the focus here is on GE modeling, some of these points are equally applicable to PE or other modeling techniques.

Fifth, EPA should not attempt to use a single GE model for all applications. Doing so would require a highly complex model that would be difficult to use and opaque to outsiders. Rather, the SAB recommends that EPA develop, over a period of time, a suite of models that are adapted to different regulatory needs. Doing so would allow EPA to produce high quality analysis with the greatest possible clarity and transparency.

Finally, both EPA and outside stakeholders should bear in mind two broad caveats regarding CGE models. First, they are designed to isolate the impact of a policy change by comparing multiple model runs to each other: typically a business-as-usual baseline is compared to an alternative in which the policy variables of interest have been changed while all other inputs are held at their baseline values. This approach is valuable because it allows the analysis to separate the impact of the policy from changes in the economy that are driven by unrelated events, such as business cycles or unexpected innovations. However, it also means that CGE models are not designed for focusing on a single scenario, as in short-run economic forecasting. Also, it means they are difficult to validate against historical data since they focus on the difference between two scenarios but only one of the two will actually be observed. To address this point, EPA should quantify, to the extent possible, the key sensitivities of modeling results to baseline assumptions, and to be clear that actual measurements of economic impacts may differ from model results due to differences in those variables. A sensitivity analysis that demonstrates that the implications of a model are not materially changed when the model is altered in credible ways would make an essential contribution to the perceived reliability of the model.

A second caveat is that CGE models rely heavily on assumptions about the structure, or functional form, of objective functions and constraints used to model the behavior of households and firms. Because relatively few observations of economy-wide historical data are available, it can be challenging to obtain precise statistical estimates of some parameters in a model, and it will also often be the case that several alternative models of a given agent's behavior could be equally consistent with the historical record. As a result, there will be ambiguity about the most appropriate specification and it will be very important to carry out sensitivity analysis with respect to key functional forms.[2]

Additional findings and recommendations follow in the order of EPA's broad groups of charge questions on the technical merits and challenges of economy-wide modeling: (1) measurement of social cost; (2) measurement of benefits; (3) evaluation of economic impacts; and (4) comparability and transparency.

1.1 Measurement of Social Costs

The social cost of a regulation is a broad measure that includes all of the opportunity costs that result from the regulation, including indirect effects that occur outside the regulated sector, or that occur in the future. Because a GE analysis can capture a much broader range of impacts than a PE analysis, GE modeling can be a valuable supplement to EPA's current approach.

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[2] See Pindyck (2013) for an illustration of the importance of assumptions about functional forms in the context of integrated assessment models used in developing measures of the social cost of carbon.

However, there are also several significant hurdles that will need to be overcome. We begin by summarizing the key benefits GE modeling can provide.

First, a GE approach can provide a fiscally-disciplined, consistent and comprehensive accounting framework that accounts for all budgetary and resource constraints in the economy. The behavior of producers and firms in the regulated market will be fully consistent with the behavior of those agents in other markets. That consistency can include intertemporal effects: a GE model can capture impacts on saving, investment, and capital accumulation, and can account for near-term actions taken in anticipation of expected future changes in regulations. Finally, government fiscal flows are consistent as well: when regulations are price-based and generate tax revenue, GE models account for the impacts that arise from the use of that revenue, whether it is used for purchasing goods, reducing other taxes, or reducing the fiscal deficit.

Second, a GE model can capture important interactions between markets, including impacts on goods that are complements or substitutes for the products produced by regulated firms. It can also capture impacts on industries that are upstream or downstream from the regulated industry: either supplying goods to it or using its output as an intermediate input. Upstream links to markets for primary factors are particularly important: a GE model can assess the impact of a regulation on wages, labor supply, the return to capital, and the supply of physical capital. Moreover, the links can extend to markets outside the U.S. through international flows of goods, services, and financial capital. GE models can also potentially capture the impact of regulation on the development or deployment of new technology.

Third, GE models are capable of accounting for potential interactions between a proposed policy and existing regulations and tax policies. A substantial literature shows that GE interactions between regulatory changes and pre-existing policies can substantially change the social cost of a policy.

Fourth, GE models are strongly grounded in economic theory, which allows social costs to be evaluated using equivalent variation or other economically-rigorous approaches. Simpler measures, such as changes in gross domestic product or in household consumption, do not measure welfare accurately and are inappropriate for evaluating social costs.

However, significant methodological barriers will need to be overcome to realize these benefits. First, CGE modeling requires comprehensive, high-quality, internally-consistent data on agents throughout the economy. Moreover, the data must be available for a substantial historical period in order to support statistical estimation of key model parameters. Building appropriate datasets from existing public sources is a complex task requiring considerable investments of time and resources, and is a significant obstacle to the development of models suitable for use by EPA.

Second, air regulations often fall on narrow segments of the economy—particular industries, production technologies, or regions of the country—and the data available for CGE modeling is usually far less detailed. In many public datasets, small industries are often merged into broader aggregate sectors, and cities and counties are combined into much larger regions, or even aggregated to the U.S. as a whole. This aggregation makes CGE analysis most straightforward for broad rules that affect most of the firms in a given sector. For narrowly-targeted regulations, however, it may be necessary to link a relatively aggregated GE model to a more detailed PE model of the regulated sector.

Third, unemployment can potentially contribute to the social cost of a regulation. To capture that cost in a GE 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 but the literature is new and more work is needed.

Fourth, the cost of building, testing, and documenting a new CGE model is high. It will rarely be appropriate to build a new model for analysis of a single regulation. Rather, EPA should focus on models that will be flexible enough to be used for multiple applications, or that can be linked to regulation-specific PE sectoral models.

Finally, an important caveat on all GE analysis 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. GE analyses should note that these constraints are not considered.

1.2. Measurement of Benefits

Although current CGE models can be broadly suitable for analysis of social costs, they are less satisfactory for evaluating the benefits of air regulations. Several significant barriers will need to be overcome for the approach to reach its potential.

First, explicit aversion to mortality risk should be included in the models of individual behavior used in CGE models. To date, analysts using CGE models have typically measured the benefits of reductions in mortality risk by comparing a business-as-usual baseline with results from a policy scenario where the proposed rule is in place. Under the policy scenario, reduced emissions and pollutant concentrations are mapped into lower mortality rates relative to the baseline, which leads to increases in the population and labor force. This approach captures the large-scale impacts of the rule on the economy's overall size and resource endowment, but it does not explicitly capture individual-level aversion to mortality risk. However, the extensive research literature underlying value of a statistical life (VSL) estimates shows that individuals are often willing to pay significant amounts for reductions in risk. For consistency with that literature, explicit preferences about mortality risk should be incorporated into CGE analysis. Doing so will provide much greater comparability between EPA's PE and GE estimates of benefits. Moreover, it will improve on EPA's traditional methodology by ensuring that estimated mortality benefits are consistent with budget constraints, demands for goods and services, and other market outcomes.

A related point is that the treatment of morbidity in CGE models should be improved. Existing studies typically use projected changes in morbidity to adjust the economy's effective labor force for reductions in sick days, and to adjust the demand for health care on a cost-of-illness basis. However, further work is needed to: (1) capture the link between health care and actual health status; (2) account for the costs of morbidity beyond the direct cost of health care and the impact on labor hours; and (3) distinguish between willingness to pay for morbidity and mortality risk reductions, which can be difficult to disentangle in empirical studies. At the same time, some potential impacts of air regulations on the health and well-being of individuals are currently too tenuous to be included in CGE models. In particular, until much more empirical literature is available EPA should not attempt to model: the health impacts of unemployment; the impact of health status on crime; or the impact of health status on the demand for goods other than health care. Finally, in the near term the EPA should be cautious about modeling productivity gains from improved air quality because existing empirical evidence is often confined to narrow segments of the economy. In some cases it may be possible to include productivity impacts via a linked PE model of a particular sector where empirical data is available. In the long term, the agency should encourage broader work on productivity impacts.

Second, the benefits of a cleaner environment beyond the changes in the labor force noted above are not included, or are not modeled well, in most CGE analyses. An extensive and long-standing literature has shown that individuals derive significant benefits from aspects of the environment with which they interact. Integrating these benefits, technically known as "use values" for environmental goods and services, into CGE models would significantly improve their usefulness for analysis of air regulations. Doing so will be challenging, however, because the existing literature on use values covers a limited set of pollutants, often focuses on specific geographic areas, and may not be able to isolate health effects from other motivations for avoiding pollution. Broader integration of use values is thus a long term task. Finally, EPA should not attempt to integrate benefits stemming from aspects of the environment with which individuals do not interact, or "non-use values," into CGE models. If non-use values are expected to be significant, they should be modeled using PE approaches.

A third challenge for CGE modeling is that the impact of air regulations on pollutant concentrations can vary substantially from one location to another, as can the demographic characteristics of the populations exposed. The local benefits of improved air quality may thus vary significantly across a region. Data limitations may make it impossible to construct a model with a high degree of geographic detail, so it may not be possible to determine air quality benefits for narrowly defined groups. However, an open question in the literature is the extent to which spatial aggregation leads to bias in estimates of national-level air quality benefits.[3] To fill that gap, EPA should encourage a model comparison project to assess the performance of disaggregated and national-level models in determining aggregate national measures of welfare.

1.3. Evaluating Economic Impacts

Many of the broad merits and challenges of using GE models for evaluating social costs also apply to their use for evaluating impacts. In this section we focus on narrower issues that are specific to impacts or are more acute in that context.

First, CGE models can be a valuable supplement to PE analysis when evaluating labor market impacts because they can track movements of workers between industries and can determine equilibrium changes in wages. With that said, there is considerable room for improvement. Most

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[3] Spatial aggregation is likely to understate the benefits to some groups and overstate them to others. It could, however, be right on average. In that case, a spatially-aggregated model might be acceptable for estimating overall benefits even though it would not be appropriate for calculating impacts at a detailed geographic level.

CGE models are designed for long run analysis and assume that wages adjust enough to balance the supply and demand for labor, thus keeping the economy at full employment. They typically do not provide information about some of the transitional impacts that arise as the economy moves to the new equilibrium, including: the extent and duration of any unemployment resulting from a regulation; the search or retraining costs as workers look for new jobs in other sectors or occupations; or temporary changes in wage differentials across occupational or skill groups.

Several methods are available for modeling labor market transition costs by relaxing the full-employment assumption. However, the most widely used and well-tested existing methods have serious drawbacks or limitations. At best, they capture general unemployment in the economy as a whole, not sector-specific unemployment in the regulated industry. New modeling approaches are highly promising, but are not yet ready for practical use. In the near term, EPA should encourage further development of CGE models able to capture short-term unemployment. Modeling long-term unemployment, particularly at the regional level, should also be considered as a longer-term research project. Finally, efforts by EPA to develop models for air regulation that include endogenous business cycles are 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.

Second, transition costs can arise in capital markets as well if capital goods cannot be moved easily between sectors and uses. Such assets may be stranded by regulation: they may earn a sharply lower rate of return in the regulated sector but not be useful enough elsewhere to make them worth moving. Modeling transition costs associated with capital is not universal in CGE models but it has a long history in the literature. Approaches include: adjustment costs in investment; putty-clay models, in which installed capital becomes specific to a particular application; capital vintaging, in which capital goods installed at different dates are differentiated and accounted for separately; or, for electric power in some GE models, detailed accounting for technology-specific capital stocks.

A third challenge is capturing detailed distributional impacts across demographic groups. Many CGE models have highly aggregated household sectors and may be unable to provide results with the desired degree of detail. In some cases, this can be addressed by linking a CGE model with a more detailed PE demographic model. Whether or not linking is used, GE analysis facilitates evaluating distributional impacts using a broad definition of income (full income) that includes the implicit value of leisure time and, potentially, other non-market components as well. These may include income support programs, home production, consumption of natural capital, and adverse impacts from exposure to environmental pollutants.

When policies have spatially-differentiated short run impacts, a model with regional disaggregation may 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. Interactions among air regulations may also need to be taken into account via spatial disaggregation: the local impacts of a proposed policy may depend on the area’s attainment status with respect to other pollutants. Spatial disaggregation of economic activity is difficult, however: in general, existing county-level data sources are not sufficiently reliable and consistent to be used in EWM. However, if detailed historical data can be obtained for individual plants, a linked CGE-PE model could potentially translate the GE effects of a policy into facility-level ramifications. Moreover, accounting for firm heterogeneity in this way could improve modeling of impacts within industries by characterizing the pattern of regulatory burdens across firms with different emissions intensities. That may be particularly desirable when regulatory impact analyses emphasize impacts on small firms.

At a broader geographic scale, GE models are an appropriate and useful method for assessing impacts on international trade and financial flows, and also for determining the degree of emissions leakage to other jurisdictions. Examples of single-country, open-economy models and multi-region global models are well established in the literature. Multi-region models are not always required but when available they allow impacts on exchange rates and global capital flows to be evaluated, as well as potentially allowing more detailed analysis of regulatory impacts on global supply chains.

Other than CGE models, the most promising approach for capturing short run impacts is DSGE modeling. Current DSGE models usually have too little sectoral detail for routine use to evaluate air regulations, but with further development they could become a valuable tool. Among other approaches, methods that evaluate impacts primarily using input-output or social accounting matrices would only be appropriate for assessing very short-run impacts of a relatively small nature, where substitution possibilities are limited and price effects are minimal. Other methods that are not appropriate for evaluating economy-wide impacts include agent-based or microsimulation models, which are typically not economy-wide, and systems dynamics models, which are not based on microeconomic foundations.

1.4. Considerations for Comparability Between Results

Because CGE models are currently better able to evaluate social costs than environmental benefits, in the near term it will often be necessary for EPA to report a mix of GE and PE results. The two should be reported separately rather than summed: it is generally inappropriate to add them since they may not have been calculated consistently. It will be particularly important to be clear that the GE results capture only a portion of total benefits, and to note the categories of benefits that remain outside the model. Although providing both GE and PE results may cause an analysis to be more difficult for outside stakeholders to understand than a single set of numbers, it is more appropriate than attempting to produce a single set of results by forcing GE modeling outside of the domain currently supported by the literature.

Over the longer term, however, a high priority for EPA should be to encourage the development of fully integrated CGE treatments of environmental benefits, with explicit modeling of the behavioral tradeoffs, or “non-separability”, between environmental and market goods. Revealed preference methods, which exploit those tradeoffs to measure the values of non-market goods, have been at the center of benefit measurement in environmental economics for over 50 years. To date, the literature integrating non-separable environmental benefits into GE models is very small, but preliminary results suggest that impacts on measures of welfare can be significant.

In moving forward with GE analysis of air regulations, EPA will need to address the fact that CGE models are complex and presenting results can be challenging. Extensive documentation of any model used should be provided, including: diagrams or flow charts showing the logical structure of the model; complete listings of equations, variables and parameters; tables of parameters indicating their values, standard errors, and how they were obtained; tables providing the baseline settings of exogenous variables; and the results of sensitivity analysis on key parameters. Results for a given analysis should be discussed in detail rather than being provided with little or no explanation beyond the model's documentation. A good approach is to explain important results using stylized or back-of-the-envelope calculations to build intuition regarding the mechanisms at work. Furthermore, when presenting modeling results it will often be useful to provide both relative measures, such as percentage changes, and absolute measures, such as constant dollar values of output. Relative measures are often easier for outside observers to interpret, but absolute measures are also important because they would be observable *ex post*. Long-term use of GE would be strengthened by the systematic assessment of a set of observable changes in economic activity that are predicted responses to regulation and which can be estimated and documented.

Finally, because the number of parameters in a typical CGE model is large, characterizing uncertainty in a transparent and systematic way is particularly important. Many well-established approaches are available in the literature. Parametric uncertainty can be addressed via systematic sensitivity analysis, Monte Carlo simulation, or the delta method. These methods are appropriate for characterizing both statistical variability and parameter uncertainty. Monte Carlo simulation and the delta method, in particular, can be used to construct confidence intervals for model results. All three approaches can be used to address uncertainties related to the model's exogenous data. Because it can be especially useful for identifying the key parameters driving a given set of results, sensitivity analysis should be a routine part of all regulatory evaluations using GE models. In addition, it can be used to compare alternative model formulations, and to address model ambiguity.

1.5 Key Recommendations

The body of the report includes many specific suggestions and recommendations. Here we list five broader recommendations that are most important overall for the development of GE models suitable for analysis of air regulations.

- First, access to high-quality data is a major obstacle to the development and use of CGE models for air regulation. To address this, the SAB recommends that EPA work with outside organizations to help establish an open-source project that would assemble a freely-available database for use by the agency, stakeholders (including the state agencies), and the modeling community. Doing so would address the single greatest obstacle to the development of high-quality CGE models for regulatory analysis. Moreover, such a database is a public good that is unlikely to be provided by actors in the private sector alone, yet will benefit public and private decision makers alike, and will greatly facilitate communication around the potential impacts of air regulations.

- Second, the SAB recommends further development of CGE models that capture unemployment. In the near term, the focus should be on short-term frictional unemployment but over the longer term, it should also include structural unemployment, particularly at the regional level. Better modeling of labor market impacts would improve CGE models for evaluating both the social costs and the economic impacts of regulations.

- Third, the SAB recommends that EPA support research on CGE modeling of the benefits of improvements in air quality, including both explicit modeling of risk aversion, and modeling of the interaction between environmental quality and household demands for market goods.

- A fourth priority is for EPA to encourage research on linking relatively aggregate CGE models to more detailed PE models of households, industries, or regions. This work should focus on understanding inconsistencies that arise from linked rather than fully integrated models. A substantial literature exists on how models can be linked, but more work is needed to determine whether the necessary approximations create large or small inconsistencies in the analysis.

- A fifth priority is for the EPA to undertake a suite of model comparison studies, and to conduct research on the impact of heterogeneity within regulated industries.

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 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 evaluate the technical merits, methodological challenges, and potential value of using economy-wide models as a supplement to these tools; and suggest paths forward that would improve the usefulness of economy-wide models for regulatory analysis. To that end, 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.

Category 1, measurement of social cost, has seven charge questions. These questions address the strengths and weaknesses of General Equilibrium (GE) models for evaluating the full social cost of regulations. Social cost differs from the direct compliance cost estimated in an ECA analysis—and is usually larger—because it includes the indirect impacts of the regulation outside the market where it is imposed. The estimation of social cost 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.

Category 2, measurement of benefits, has eleven charge questions. GE analysis has been used less extensively for estimating environmental benefits than for social costs. The challenges of estimating benefits are greater in some respects, including issues related to 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 3, evaluation of economic impacts, addresses distributional outcomes: i.,e., how the benefits and costs of regulations are distributed across sectors and households. This category has 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). Finally, category 4 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.

The chartered SAB held its quality review on August 29, 2017. This report provides the findings and recommendations of the SAB in response to the charge questions (Appendix A).

2.1. An Overview of Economy-Wide Modeling

EWM 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 sub-model. 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.

Several types of EWMs have appeared in the literature including: input-output (IO) models, macroeconometric models, hybrid IO-macroeconometric models, general equilibrium (GE) models, and dynamic-stochastic general equilibrium (DSGE) models.[4] The most suitable approach for measuring social costs, and the one that has been used most extensively in the literature for environmental policy analysis, is GE modeling. Other methods should not be used for evaluating social cost but may be suitable for evaluating certain regulatory impacts in particular circumstances.

The EWM approach that has been most widely used for environmental policy analysis is 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 the reasons why EWM yields useful information above and beyond that provided by ECA and PE analyses. Henceforth, for clarity, in this report we will generally refer to economy-wide models as GE models. When discussing computational rather than analytical (theorem-oriented) 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 a detailed 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).[5] ECA is usually needed because the benefit-cost analysis must be done before the regulation takes

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[4] Some GE models use linear programming or other engineering optimization techniques to drive technology utilization in electric power generation or other energy sectors.

[5] See NRC 2012 for a detailed discussion of the importance of using reliable cost estimates as the starting point for subsequent analysis.

effect and thus before the actual pattern of responses to the proposed new rules can be observed.[6] Typically, the ECA 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 model. 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 are 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 most. 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 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.

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 GE is a highly flexible approach, GE modeling faces few circumstances where it is categorically inappropriate: with enough data and development time, almost any feature could be

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[6] The exception would be policies that mimic events with 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.

incorporated. As a result, when responding to broad questions we will often discuss the appropriateness of GE modeling with respect to the following time periods:

> *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 within 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 ECA and treating the engineering costs as the social costs of the policy, or (2) augmenting the ECA with a 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 PE 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 alternative formulations are frequently used by EPA analysts. GE analysis is much less common, in part because the methodology has evolved over time. 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. Thus, the Agency now faces many differences among various CGE models, as well as differences among engineering models and PE models. And, of course, some very useful analytical GE models can be as simple as a PE model, while still capturing the important interactions and budget consistency of GE analysis.

A possible disadvantage of the CGE approach is its relatively aggregated structure with less detail on each industry than offered by some engineering or PE 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 pursue efforts to add unemployment as a feature of CGE models. In the long term, as the literature on behavioral economics matures, we also recommend that EPA integrate 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, although significant theoretical and empirical work would need to be done to provide a rigorous basis for such changes. Because the CGE methodology is very flexible, virtually any feature, such as those listed above, can be added with sufficient additional data, programming, and computational resources.

Overall, we caution against placing too much emphasis on choosing between a CGE approach and a PE approach, as posed in this charge question. The more important choices are among particular model features appropriate for the problem at hand. Moreover, 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 be sufficient for analysis of a policy in one market that is not expected to affect other markets throughout the economy, and for instances where consumer responsiveness to higher production costs, averting behavior, or substitution in consumption are not considered to be 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, or regulation). Distortions arising from externalities could also be captured in models where environmental quality is not separable from market goods.

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

    - This is especially true where improvements in environmental quality are not separable from market goods in utility. In that case, environmental quality may affect demands for goods, which would lead to indirect 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 GE 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 PE 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 GE effects of T_i in *other* markets. Each such 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 that are 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 GE welfare effect for small changes, but the use of a CGE model can: (1) capture those GE 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.[7]

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.[8] 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 non-market environmental services. Although existing empirical data is inadequate for parameterizing a full range of environmental goods in CGE models,

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[7] This approach can be extended to include the impact of taxes on non-market goods when market and non-market goods are not separable in utility. However, the marginal willingness to pay for the environmental good is required. See section 4.2.

[8] Changes in a non-separable environmental public good are not represented in equations above because those equations consider only *n* market commodities, but the 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.

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 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, these models usually have 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 (WTP) for separable non-market goods must consistent with household budgets.[9] Treating PE measures of marginal WTP as constants when measuring the benefits of non-marginal changes in environmental quality ignores the effects of the budget constraint on the marginal willingness to pay.[10]

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

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[9] If the household has access to capital markets and is able to borrow or lend, the bound on WTP is imposed by its intertemporal budget constraint rather than its current income. However, such constraints are included in intertemporal GE models.

[10] Note that budget constraints do not apply to some PE measures used for evaluating risk. In particular, willingness to accept (WTA) is not bounded by income.

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

> *Charge Question: Relative magnitude of the abatement costs of the rule.*

Analysis of an environmental policy with direct effects on one sector may require a GE model if it has significant indirect effects on other sectors. The increased cost of producing output in the sector that is the target of regulation may affect demands for other goods that are complements or substitutes, or the cost and quantity of production in activities that use the target output as an intermediate input (forward linkages). The policy may also affect demand for the target sector’s intermediate purchases of goods produced by upstream industries, or its hiring of factors of production (backward linkages). These linkages are the conduit for indirect effects on prices and quantities in commodity and factor markets that ripple through the economy. A “larger” policy with greater direct distortionary impact on production decisions in the target sector will also have larger spillover GE effects.

However, the magnitude of the policy alone is *not* a good indicator of whether analysis requires a GE model. Given a target sector with sufficiently strong forward or backward linkages, even a policy whose direct effect is small can have indirect effects elsewhere that are of comparable magnitude. Conversely, if these indirect effects on other markets are a small fraction of the total impact on the economy, then the analyst might appropriately use a PE model of the direct effects only. The challenge is that the absence of a GE model can make it difficult to predict whether GE effects are likely to be material. The key criterion is whether the target sector has minor or non-existent backward and forward linkages. If so, then the bulk of the regulatory impact can be captured using a PE model of the regulated sector.

Once the regulated sector incurs pollution abatement costs that are non-trivial relative to the value of the economy’s aggregate factor income, with non-trivial demands for labor or capital, then the backward linkages will induce shifts in relative factor prices and consequent adjustments in other sectors’ factor demands. 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. In this case, the policy could have larger feedback effects 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.

One might then ask how the magnitude of an environmental policy might matter. In an industry with non-trivial forward and backward linkages, a larger policy that requires extensive pollution reduction effort pushes the sector's producers up their marginal abatement cost curves and induces large changes in the quantities of sectoral output and inputs relative to their no-policy equilibrium values. These bigger distortions will incur larger direct and indirect costs. In this regard, it is important to distinguish between the level of the policy and the change in policy. With a large pre-existing tax on pollution, for example, analysts can differentiate the equations of an analytical model to solve for the GE effects of a *small* change in the tax that has high marginal abatement costs. General equilibrium effects on other markets are even more important if the markets in question have significant pre-existing distortions (such as taxes, subsidies, externalities, or market power). Goulder and Williams (2003) suggest that while the absolute size of the error caused by ignoring general-equilibrium effects grows as policy shocks get larger, relative error shrinks (i.e., the error as a percentage of the estimate). A CGE model may still be needed if the policy change itself is large, or if the analysis needs to consider many sectors, multiple consumer groups, the input-output structure of intermediate demands, or other details.

In practical terms, the implicit precision of a CGE model will limit its ability to provide useful results for very small shocks.[11] 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.

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

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

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) challenges remain 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

Charge Question: 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. Thus, strong reasons suggest use of such models for analysis of polices that are likely to affect those variables. PE 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 PE 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, in the manner of 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 GE 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) "Regional or State-Implemented Emission Targets", such as the primary Ozone National Ambient Air Quality Standard (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, respectively. 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.

No hard and fast rule for the number or type of sectors affected justifies a CGE approach; rather, the considerations should be those described in Section 3.1: strong cross-price effects between markets, and pre-existing distortions present in those markets. With weak cross-price effects and small distortions, a multi-market PE 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. A *prima facie* case can be made 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 that 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 3.4 under vintage capital or in Section 3.6 on linking). 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 GE 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, important transition costs may be 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 analysis. Considering the specific problem of representing those transition costs related to stranded assets (capital) that result from discrete production processes or separate vintages of capital, 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 (or below it, for technologies that improve energy efficiency). 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 GE 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?*

Multi-period CGE models have two distinct characteristics that are relevant here: (1) the behavioral specifications they use for intertemporal decisions such as saving and investment, and (2) the assumptions they impose about how agents form expectations. These characteristics split models into three broad classes: *perfect foresight*, *imperfect foresight*, and *recursive dynamic*. Perfect foresight models assume that savings and investment decisions are based on intertemporal optimization, and that the agents making those decisions have expectations that are accurate—that is, they correctly anticipate how a policy change will affect the future economy.[12] Imperfect foresight models also base behavior on intertemporal optimization but assume that agents are less accurate when forming expectations. One approach is to impose myopic expectations: agents believe that future conditions will be like the present. Another approach is partial adjustment: agents have expectations that gradually converge to perfect foresight over a number of years. Purely recursive dynamic models, in contrast, use specifications other than intertemporal optimization to drive savings and investment. For example, some models in this

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[12] The term "perfect foresight" is used here in a narrow technical sense and is not meant to indicate that every individual in the economy is free of the biases and misperceptions identified in extensive literature following Tversky and Kahneman (1974). Rather, it is used to mean that agents in the economy, in the aggregate or on average, are not systematically wrong about future events.

literature assume that households have a fixed marginal propensity to save out of income while others model saving by using the extended linear expenditure system. Because intertemporal optimization is not used to drive behavior, recursive dynamic models have no role for expectations. Finally, some models in the literature are hybrids of these types: the Economic Projection and Policy Analysis (EPPA) model, for example, can be used as a perfect foresight or recursive dynamic model, but even in its recursive dynamic form it allows for perfect foresight in some contexts and is thus not a purely recursive dynamic model.[13]

None of these approaches fit the empirical data perfectly, and the macroeconomics literature has many competing models of both saving and investment. Actual saving and investment tends to be less responsive to changes in expectations than a pure perfect foresight model would predict, but more responsive than would be predicted by a model with myopic expectations or recursive dynamics.[14] From the perspective of CGE modeling, a key challenge is the underlying heterogeneity of households and firms. For example, intertemporal optimization is likely to be a good explanation for saving by some households while simpler utility functions may be better more appropriate for others. Expectations will differ across households as well. Some real-world households have a sophisticated understanding of the economy and would be best modeled as having perfect foresight. Other households are likely to have myopic expectations, and still others may have expectations that are fundamentally incorrect, such as expecting that a policy will cause the economy to grow when it would actually shrink. No single assumption about expectations fits all three groups, and thus no single mechanism will always be most appropriate. Moreover, any given mechanism will always be subject to the critique that it fails to fit the behavior of one subgroup or another.[15]

Further, representing any degree of foresight beyond myopic expectations within a model significantly increases that model's dimensionality and computational complexity.[16] As a result, perfect foresight models often have less detail than recursive dynamic models: they have fewer and more aggregated sectors, households, and regions. The choice between models may thus involve a tradeoff between detail and foresight. If the focus of the analysis requires a very high

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[13] In particular, the recursive dynamic form of EPPA allows for a form of perfect foresight arbitrage over carbon dioxide taxes or emissions permit prices.

[14] See, for example, Campbell and Mankiw (1990), which suggests that aggregate consumption is best explained by a mix of agents, some whose behavior is consistent with the permanent income hypothesis and some whose behavior is driven by current income instead. Similar empirical issues arise with investment. See, for example, Chirinko (1993) or Cummins et al. (1994) for a discussion of the difficulties that arise in trying to reconcile aggregate investment data with the adjustment-cost model of investment.

[15] It should be noted that building in an assumption that expectations are incorrect in a permanent and predictable way would mean, in principle, that simple paternalistic government policies could reliably produce welfare gains by offsetting the mistakes made by agents with imperfect foresight. Moreover, policies that unintentionally have the effect of offsetting systematic errors in expectations would appear more beneficial than they actually: some of the apparent welfare gains would arise from the expectational effect. In practice, such gains seem unlikely: at an aggregate level, expectations are more likely to be unpredictably wrong—for example, they may be randomly distributed around a mean corresponding to perfect foresight. No existing models use such an approach but it would be a good candidate for future research.

[16] Models without foresight or with myopic expectations involve difference or differential equations that take the form of initial value problems. Models with more sophisticated foresight are two-point boundary value problems and generally require more complex solution algorithms.

degree of specific sectoral or technology detail and doesn't involve significant anticipation of future policy changes, then it may be appropriate to use a technology-rich recursive dynamic approach: little would be lost from the absence of intertemporal optimization and much could be gained from the additional detail.

However, purely recursive dynamic models (or models with myopic expectations) rule out by assumption any anticipatory actions by agents in the run up to a new regulation or prior to announced changes in existing regulations that are designed to change over time.[17] Recursive dynamic models are therefore less appropriate when anticipation may be important. Forward-looking consumers, for example, borrow or save money in order to equate the discounted marginal utility of consumption over time. This aspect of behavior results in consumption smoothing: anticipated shocks in income are smoothed out by altering consumption and saving in advance of the shock. Models without foresight will not capture these effects: consumption and saving will not change until the shock actually occurs.

In general, a strong case can be made for using intertemporal objective functions to drive saving and investment. Other modeling approaches effectively impose tighter restrictions on behavior by ruling out intertemporal substitution. The impact of intertemporal substitution can be large. For example, Babiker et al.'s (2009) comparison of intertemporal and recursive-dynamic versions of the same multi-region, multi-sector CGE model shows that while a multi-decade climate change stabilization policy induces similar sectoral and price behavior in the two versions, global macroeconomic costs are substantially lower in the forward-looking version since households have an additional margin on which to adapt to the policy: i.e., shifting consumption between time periods.

When possible, it would be valuable to conduct sensitivity analysis on how a given model represents expectations. A model normally used in a perfect foresight configuration, for example, could be run with myopic expectations instead.[18] Such an analysis would shed light on the relative importance, or unimportance, of anticipation of policy changes. Moreover, in some circumstances it would be worthwhile to simulate regulations that evolve over time as a "phased" or "rolling" sequence of shocks to the economy, where actors inter-temporally optimize within each phase of the policy, but changes in the attributes of succeeding phases are not anticipated.

Such sensitivity analysis would help clarify the domain of problems for which anticipation effects are unimportant, and thus where recursive dynamic models are most applicable. Those results would be particularly valuable for understanding the strengths and weaknesses of subsequent analyses for which only one type of model or the other was available. 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.

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[17] As noted above, EPPA, which is usually described as a recursive dynamic model, is actually a hybrid that includes perfect foresight by implicit agents who carry out carbon tax or permit price arbitrage.

[18] The ability to switch expectations-generating mechanisms is not common but can be built into perfect-foresight models. A model with this feature is G-Cubed; see McKibbin and Wilcoxen (1999, 2013).

In some circumstances it may be desirable to link a relatively aggregated intertemporal GE model to a more detailed PE 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 is an example of soft linking and is discussed 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 GE of the economy under consideration.

Trade is important because the U.S. economy is large and relatively 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 alter the GE 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, and the economy's openness to flows of financial and physical capital.

Structural assumptions regarding demands for imports may also 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 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 international trade 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 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.

These trade structures 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. Significant literature and debate surround 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 another 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. Dynamic multi-region models provide 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 capital flows and thus change stocks of debt and future interest payments. Dynamic modeling approaches can represent various restrictions on international capital flows, all the way down to a period-by-period balance of payments constraints. It is worth noting, however, that intertemporal welfare calculations are more difficult in the presence of restrictions on capital flows, as they would be with other quantity constraints.

The methods discussed above largely address 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 U.S. assets will lead to capital outflows, a deterioration in U.S. 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 U.S. in anticipation of policy.

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 inappropriate, and care must be taken to accurately represent 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 trade elasticities assumed within the model.

Stepping back from the details, trade responses have importance beyond analysis of the economy-wide policy burdens. Given that GHGs are embodied in internationally traded commodities, there is a large and growing body of work that attempts to quantify the tariffs, or border carbon adjustments, that might be used when a subset of countries pursues climate mitigation policies. These tariffs are needed to offset international leakage of greenhouse gas (GHG) emissions (and to shore up output and capital returns in abating sectors). 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 EPA is evaluating 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 a CGE model can do well.

Model closure must also address endogenous adjustments in factor supplies; that is, endogenous supplies of labor and capital. In single- or multi-sector PE models, factor markets are typically assumed to have an infinitely elastic supply at constant marginal cost. That is, changes in factor demands occurring within the sector are assumed to have no influence on the rest of the economy. Spillover effects on the broader factor market could be modeled in PE by introducing elastic factor supplies. However, this method does not capture 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.

Further, the vast double-dividend/tax-interaction literature looks at how GE interactions between government policy changes and pre-existing distortionary taxes can substantially change the net economic costs of policy (see Goulder, et al. 1999). This highlights 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). In turn, this highlights yet another aspect of model closure, i.e., assumptions regarding the government's budgetary balance and fiscal components of regulations that are price-based and which 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 model selection is to consider the options shown in Table 1. For each option, the "Dev. Cost" column gives a rough ranking of the resources required to develop the model (i.e., theoretical specification, parameterization and development of key datasets for model inputs); and the "Use Cost" column indicates the marginal cost of applying the model to a given analysis (i.e., developing the appropriate sets of inputs and analyzing the results).

Table 1: Analytical Options

Option	Description	Dev. Cost	Use Cost
A	Existing CGE model that is well-suited to the analysis	Zero	Low
B	Adapted version of an existing CGE model	Medium	Medium
C	Existing CGE model *not* well-suited to the analysis	Zero	High
D	New CGE model developed for the purpose	High	Medium
E	Small analytic GE model	Low	Medium
F	Omit economy-wide analysis	Zero	Zero

Options A through D are attractive because CGE models provide detailed results and impose consistency across goods and markets in accounting for the impacts a regulation; this requirement brings discipline to the entire regulatory impact analysis. Properly conducted, CGE modeling is capable of providing a transparent and rigorous way to track the economy-wide costs of regulation, and is the only way to consistently estimate aggregate welfare impacts.

The strongest case for CGE analysis is option A: when an appropriate model is available, the benefits of an economy-wide analysis are available at low cost. In contrast, option D should only be used when: (1) GE 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. It is costly to develop a new CGE model, and it is more difficult to carry out an analysis with a new model than with one that has been used extensively.

Options B and C lie between these two, and are likely to be the alternatives most frequently considered by EPA. When choosing between B and C, if an analysis is likely to be done repeatedly, option B, with higher development costs but lower marginal costs, will usually be better. Option C is most appropriate for stand-alone analyses for which GE impacts do not warrant the development of a new model. However, bear in mind that option C's low development cost is offset by the high costs of using a model for a task other than that for which it was designed.

Finally, if no appropriate model is available and the regulation in question doesn't warrant the development of a new model, option E may be appropriate. Analytical 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, it is not a trivial task to build a small model suitable for a given analysis that will stand up to scrutiny. In addition, extracting useful results from an analytic model can require sophisticated mathematical analysis. In contrast, useful results can often be easily extracted from the numerical output from a computational model. Finally, option F is appropriate for instances in which it is unlikely that significant costs would be omitted from a PE analysis.

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 EWM is large, characterizing uncertainty in a transparent and systematic way is particularly important.

Although it is not often done, the statistical uncertainty in CGE results can be characterized just as standard 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 (e.g., information quality with respect to data, models and results) to the specific (e.g., 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 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 an 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.[19] 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 but the literature on validation methods for GE models is quite limited. While other methods of analysis (e.g., econometric models) have well established, built-in indicators of statistical validity, many CGE models are constructed by linking parameter estimates from disparate sources in the literature to data sets of inter-industry flows of goods and services having few observations over time. In some cases, the models may be saturated in terms of the number of parameters relative

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[19] See the glossary entries for definitions of “accuracy” and “precision” as the terms are used in this document.

to the information provided by the data (as discussed in more detail below). Very few GE models are based on sufficiently robust historical data for conventional goodness-of-fit measures to be applied (see section 6.5 for recommendations on ways to improve the available data). Approaches for addressing model validation are discussed further in Section 6.4. In the near term, a key priority is extensive sensitivity analysis to document the features and parameters of the model that are most important in determining its results.

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 terms “reliable” 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 reviewed by an SAB panel (the Regulatory Environmental Modeling Guidance Review Panel). However, the Panel’s charge did not ask it 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, and input data (NRC 2007, p. 186, Box 5-7).

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 U.S. 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). It provides 40-70 sectors (depending on the year), which 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 for 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 U.S., 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 EWM. 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. For many regulations, it will not be possible to use a GE model alone: linking with a more detailed PE model will be required in order to provide adequate detail (see Section 3.6).

3.3.3. Representation of labor transition costs

Transition costs in the labor market, 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, no particular reason suggests 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 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 sub-model 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. Employment aspects of economy-wide modeling are discussed in more detail in Sections 5.4 and 5.5.

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 challenges involved in observing the expectations of agents in the economy. Large, complex models can also be difficult to use as an operational tool. The problems are as mundane as long solution times (and frustrating debugging cycles), or as fundamental as the difficulty of providing intuitive explanation of model outcomes. Including features like spatial resolution or multiple households can provide information on distributional issues, but it complicates the communication of model results for aggregate (representative agent[20]) welfare impacts. 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

We list below 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 alternative choice and to appropriately acknowledge any limitations of the model. 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 for the data available to determine its behavioral parameters.

2. As discussed in Section 3.2.5, an important model choice is the assumption about the agent's planning horizon and degree of intertemporal foresight. As a long-term strategy, it is important to have the flexibility to model outcomes for different planning horizons, including perfect foresight.

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, and will increase the credibility of its 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 regarding the existence and quantitative nature of existing distortions is current good practice and should be incorporated into current work plans.

5. Theory suggests important endogenous impacts of policy on productivity growth and technological change. Modeling these impacts explicitly can be challenging, but should

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[20] See the glossary for a brief definition of representative agent.

be considered. Incorporating these impacts as an integrated part of an applied model is a long-term priority but current analysis should acknowledge them.

6. Extensions to models that reflect interregional or international factor movements can lead to significant complications, but spatial price changes will indicate migratory pressures that can be important. 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. Incorporating subnational social accounts is desirable for reporting spatial impacts, however the data available to do so are often based on apportioning national benchmark accounts in a way that diminishes the desired spatial heterogeneity. Any time subnational accounts are used it is important to systematically verify and validate the data for the key industries and commodities impacted by regulation.

8. Regulation has public finance implications and interactions, and this requires additional modeling choices regarding the instruments that control the size of the government and potential interactions with other parts of the economy. Sensitivity analysis for these choices is possible now and would be useful for any report. In intertemporal models, however, a longer-term issue involves the benchmark evolution of government debt. A transparent standard treatment of the benchmark debt evolution should be established, but longer-term alternative treatments might also be explored.

This list is not intended to be exhaustive, but rather highlights certain considerations in modeling relevant policy questions. It is also important to foster and maintain close connections with others engaged in similar research. To this end, it is essential to adhere to principles regarding peer review and use of publicly available data and models in order to develop credible analyses; this topic is discussed in more detail in Section 6.3. Continued participation of EPA analysts in professional meetings and in preparation of peer-reviewed publications will be important in keeping EPA in touch with the broader modeling community.

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 aggregated to capture air basin-specific regulations. It is also difficult to predict what each state will do to comply with the NAAQS, particularly for those compliance actions states must take that are not attributable to specific control measures and which may cost more than EPA's upper-bound action. However, this difficulty is not unique to CGE analysis: other methodologies must confront it as well.

In addition, models—whether PE or GE—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, for numerous reasons:

- limited capacity to determine the cost-minimizing compliance strategy; few regulated entities have sophisticated models and compliance staff available 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 EWMs 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. The potential arises 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.

Another approach that can be used for non-price regulations is capital vintaging. Most GE models do not distinguish between capital goods produced at different times apart from adjusting older stocks for depreciation. In contrast, vintage capital models treat capital goods from different periods (alternative vintages) as imperfect substitutes for one another. Each vintage is tracked separately and may have specific characteristics, such as energy efficiency or emissions intensity. Because they involve tracking multiple capital stocks with differing characteristics and determining the utilization rate of each vintage at each point in time, vintage capital models can be challenging to implement. However, the approach can be well-suited to evaluating some types of regulation, especially rules with forward-looking performance-based standards intended to force development and adoption of new technologies.

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, potential challenges are associated with implementing this approach (although these challenges exist when modeling quantity instruments as well): for instance, identifying what should be taxed when it is not clear which sectors will be affected and by how much (such as under the ozone NAAQS); implementing the tax when input process may change in response to the regulation; and addressing 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 a specific technology that it expects firms will use to comply with the regulation. Introducing this information into an economy-wide model can be challenging because the compliance technology is usually more granular than the representation of production in the model. If necessary, an approach linking the economy-wide model to a detailed sectoral model, as discussed in Section 3.6, may be appropriate.

Greater granularity may also be needed in economy-wide models to represent other kinds of regulation. For example, in the case of CAFE standards (an example of the technology-forcing regulations mentioned above), distinguishing between light trucks and passenger cars is critical, and some models have only a single sector for all motor vehicles. However, the importance of this level of detail is not unique to economy-wide models. Engineering analysis of CAFE standards, for example, failed to account 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.

In the end, however, analyzing most non-price regulations in a CGE model will involve some degree of compromise. For example, to comply with CAFE standards, designers changed many vehicle attributes (Ito and Sallee, 2014) and did so throughout the product line. It will be possible to approximate the impact of these changes on buyers through a change in the effective overall cost of vehicles but it will generally not be possible to pick up the nuanced changes in intermediate inputs that would accompany the design changes.

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 impacts of the regulations on the consumer or the producer, 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).[21] 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. Doing so requires 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

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[21] 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.

optimizing behavior on the part of the consumer).[22] Its use in a PE framework is only appropriate, however, 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.[23] 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 because those models do not include adequate detail on consumers. By construction, engineering models measure a subset of regulatory costs–the direct compliance costs to the firm—and do not capture the broader impacts on household welfare measured by EV.

A second potential drawback is that EV is not a familiar concept for non-technical readers. People have experience with income, prices, and macro concepts such as GDP. In contrast, EV is a hypothetical value from a thought experiment: how much would someone pay to obtain an improvement in air quality? It can be challenging to explain in a way that can be grasped easily.

The two main alternatives to EV as a welfare measure—household consumption and GDP—are seriously flawed. Both are important variables that should be reported as part of an analysis but, as discussed below, neither concept is designed as a measure of welfare and neither should be used that way.

Using changes in household consumption to measure welfare only captures welfare provided by marketed consumption goods. Omitted from this measure are the value of leisure time and home production, which are 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)

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[22] 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.

[23] 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.

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 of 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 thus 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. However, even though those measures do not capture 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. Finally, it is usually best to provide all measures in constant dollar terms, and it is important to be clear about exactly which price index is being held constant (usually the model's numeraire).

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 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), models can be linked in many different ways 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

Soft linking refers to using computationally-separate models in tandem by passing a subset of variables back and forth between the two and iterating until a joint solution is achieved. A typical application might be to override the specification of a key sector in a CGE model with a much more detailed PE representation. Key variables from the CGE model, such as factor prices and the overall demand for the sector's output, are passed to the detailed PE model. The PE model is then solved, conditional on those variables, for the sector's mix of inputs and the unit cost of its output. Those values are passed back to the CGE model, which is then solved conditional on them, producing new factor prices and output demands. New values of those variables are passed back to the PE model and iteration continues until both models are consistent.

Soft linking is used when the PE model is sufficiently complex or different in structure from the CGE model that it cannot easily be merged directly into it. As a result, it can be challenging to carry out because the outputs from each model may differ significantly from the inputs needed by the other (e.g., in the definition of industries and goods, the units used, price normalization, and so on). 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 for use in the GE model difficult and can make it impossible to use feedback loops to take into account changes in sectoral input and output prices. To make the results replicable, the linking procedures and the sectoral model must be documented adequately, and the consistency between the sectoral and GE models must be explicitly addressed. In particular, use of proprietary sectoral models will limit opportunity for replication of results only to researchers having access to the proprietary model. Soft linking can be a useful approach, but each instance must be evaluated to ensure that the linkages between the models are appropriate.

Separate and unique issues are associated with soft links between models of the natural systems that receive emissions and the resulting changes in environmental quality. As noted earlier, limited attention has been given to evaluating these soft links. Smith and Zhao (2016) showed in a small simple model that such soft links may be equivalent to assuming separability of all non-marketed environmental goods.[24]

Summary function approach

The summary function approach 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 that represents 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 must be exercised in the application of MACs and interpretation of results. First, the steps used to construct a MAC should be clearly stated and any critical assumptions should be subject to sensitivity analysis. For example, MACs are usually constructed for a specific implementation year and assume fixed input prices over the life of the technology; if those prices or the underlying technology change significantly over time it may be necessary for different years to use different MACs. Second, some external MACs in the literature show that negative-cost abatement is possible: for example, some studies argue that certain energy-efficiency technologies save more than they cost. Using these curves is difficult

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[24] That is, simple soft linking may not be able to capture behavioral tradeoffs individuals make between environmental quality and market goods. Under those circumstances, improvements in environmental quality may make individuals better off but would have no effect on their behavior. As discussed in Section 4, to improve the modeling of benefits in GE, it will be necessary to move toward non-separable treatment of environmental goods, and hence away from overly simple linking approaches when incorporating feedbacks between natural and economic systems. Section 6.5 recommends that research on non-separable benefits should be a high priority for EPA.

because they are inconsistent with the cost minimization behavior usually imposed in CGE models.

The summary function approach is appropriate when 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

Sequential calibration is a more sophisticated way to link two models and it has been 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 GE impacts of the regulation. Another complication is that the engineering model will often incorporate more granular concepts of prices for inputs or for the goods being produced; for those cases a formula will be required to transform multiple prices in the engineering model into a single price in the CGE model and vice versa.

Hard linkages or disaggregation of the CGE model

In order to establish greater consistency between a technology-rich bottom-up model and a CGE model, another option is to set up a hard link between the models (via a superstructure that solves the models simultaneously) or to integrate the bottom-up technologies directly 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). This approach 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, it is now possible to capture the factor market impacts of air regulations. This kind of disaggregation is time consuming and difficult, because it requires bridging engineering and economic data and concepts. Fundamental differences between the models will usually mean that some aggregation of the detailed model will be necessary and full consistency between the models might not be achieved. 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, developing hybrid models have potential – 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), which is fully integrated, and with many of its components based on time series estimation. It also includes some aspects of GE modeling in its labor market module and can readily be used in cases where policies operate through non-price mechanisms, such as mandated changes in technology.

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, macro-econometric models (and other models that include a reduced-form macro-econometric component, such as the REMI model and other conjoined I-O/macro-econometric 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 in cases with 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.[25]

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[25] CBO and JCT use this approach only for proposed legislation likely to have impacts far larger than the vast majority of air regulations. We mention it to illustrate the value of parallel models but not to 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.

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, all are fairly aggregated. This may present a problem when modeling pollutants with specific localized effects in a national analysis. 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 affect potential 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.

Conversely, if GE benefits of air regulations are expected, the next question is whether the feedbacks themselves will vary spatially. If such GE effects are not expected to vary across space, then the aggregated approach may be adequate. If the feedbacks are likely 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 GE effects. A channel through which such benefits may have GE effects is through the time endowment, which is the total time the population has available for work or leisure. 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 GE 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 PE analyses (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 emanates 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 SAB report, 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 Zhao (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 for estimates generated using WTP measures, an important consideration is the degree of separability between non-market benefits (associated in part with changes in mortality risks) 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 that are based on the mortality risk reductions generated by the regulation. The projected improvement in environmental quality and the dose-response functions that underlie partial equilibrium benefits estimates, can be used to 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 WTP or willingness to accept (WTA) for risk reductions.[26] These estimates are often based on hedonic wage models that attempt to isolate the effect of differences in on-the-job risk across employment types on market wages (US EPA, 2010f).[27] 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 an estimate of the marginal value placed on a reduction in risk (often expressed as the 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, and reconciling them is important for several reasons such as: characterizing the type of benefits (mostly premature mortality risk

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[26] Because we are focusing on the difference between PE and GE analysis, for readability we will generally follow EPA's charge question and use the term WTP for all valuations of marginal risk reductions rather than switching between WTP and WTA. However, WTP and WTA have important differences. An agent's WTP should be constrained by the agent's budget: that is, it should be consistent with the agent's resources as well as with the agent's spending on other goods. In contrast, WTA is not constrained by the agent's budget.

[27] See the glossary for a brief definition of "hedonic wage model".

reductions); finding GE effects (if so, primarily through the time endowment); finding whether these effects vary across space (not if labor supply is mobile or beneficiaries are retired). An important issue is that the magnitude of effects derived from WTP measures are such that important GE impacts are likely. 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 WTP, the key point here is that WTP measures of benefits are often substantial, in which case GE consequences are likely. Moreover, GE effects arise 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 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 WTP 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 WTP for an incremental reduction in the risk of death, the marginal WTP 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.[28] 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

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[28] 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.

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.[29]

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: the studies underlying VSL estimates typically evaluate risk changes in isolation from other changes an agent might make in spending patterns. Moreover, conceptually VSL captures WTP for a small change in risk; that is, for changes involving relatively small amounts of virtual expenditure relative to income. Using VSLs in PE to evaluate the benefits of risk reductions involving large changes in virtual expenditure may thus produce incorrect estimates of benefits by either: (1) overlooking impacts on complementary or substitutable market goods when preferences are non-separable; or (2) failing to account for diminishing marginal utility when large changes are involved. In contrast, GE analysis can, in principle, account for both. 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 the benefits that might accrue 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-

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[29] 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.

counting of benefits where overlap between categories exists. In addition, it can provide useful information about how different categories of benefits are related.

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 for 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 in order to reconcile PE and GE 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.[30] 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.[31]

Two key pieces of information would be required to credibly parameterize such a model: an estimate of aggregate marginal WTP 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

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[30] To be precise, the result of this calculation is a value technically known as "full income" that functions as a constraint on the household's choice over bundles of leisure and consumption goods. It does not include any surplus from either leisure time or consumption goods, and is not intended to be, nor it is used as, a welfare measure.

[31] 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 issues remain to be explored and the literature is not sufficiently mature for near-term use in regulatory analysis.

of elasticity assumptions.[32] Recent advances in the modeling of averting behavior would offer reduced-form estimates that could be used to bound the range of values used for the elasticities.

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.

Importantly, 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 an 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 they are able to present a more complete picture of the operative policy responses. Moreover, a CGE model provides a tool through which researchers can reduce the tradeoff between precision and completeness by testing which interactions matter and which are unimportant. If GE 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 GE 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 with respect to both concentrations of pollutants and the demographic characteristics of exposed populations. 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 also discusses 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 status to changes in employment status that may result from regulatory changes.

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[32] 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.

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 $PM_{2.5}$ 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 mortality and morbidity as changes in the time endowment (the total time available to households for allocation to labor or leisure) is technically feasible and numerous studies support the approach (Burtraw et al., 2003; Yang et al., 2004; Matus et al., 2008; Nam et al., 2010, Matus et al., 2012; Saari et al., 2015).[33] However, other channels for capturing the impacts of reduced particulate matter (PM) having a diameter less than 2.5 micrometers ($PM_{2.5}$) exposure should also be considered including labor force participation (the household's choice about whether to allocate any of its time endowment to labor) and changes in expenditures on health care services. Mortality and morbidity impacts can be modeled as changes in market effects (e.g., lost wages, and expenditures on health care) plus some valuation of the non-market effects of illness (e.g., 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 studies that incorporate the 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 non-market services (see discussion in Sections 4.5 and 4.9).

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[33] It should be noted that the time endowment approach typically accounts for only part of the costs of morbidity: lost work time. Impacts on quality of life would need to be accounted for via other mechanisms.

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. CGE economic model in a study by Saari et al. (2015), in which 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 each require validated epidemiological relationships between air pollution concentrations and the resulting health impacts, and the valuation of 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 between using a CGE and 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 and WTA estimates for reduced mortality risk are discussed in Sections 4.2 and 4.5. 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 assumed by EPA to be the result of 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).

Moving to other representations of direct impacts will be challenging. The best-developed literature for valuing air quality using methods other than the VSL approach is hedonic pricing. Clear and long-standing empirical results from hedonic property value models show that air pollution affects housing values. An early meta-analysis by Smith and Huang (1995), more recent 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. That said, several difficulties arise in extending this literature to the national level, as would be required by CGE analysis. Existing models: (1) may not provide sufficient resolution in terms of air chemistry to distinguish between the impacts of different pollutants; (2) cover only a limited subset of urban areas; (3) cannot distinguish health effects from other motivations for avoiding air pollution; and (4) may be vulnerable to confounding spatial effects from unobserved variables.

However, it is possible to use hedonic property value estimates as part of a check on the plausibility of benefit assessments based on the conventional VSL strategy. For national scale policy analyses involving important rules, the use of estimates from multiple methods could be carried out in tandem with 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. In principle, combining hedonic estimates of property value and labor market impacts is also possible since the two affect different margins. See Kuminoff, et al. (2013) or Smith et al. (2002).

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 GE 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.[34]

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[34] See Smith and Carbone (2008a,b) for additional work on integrating changes in risk into CGE models.

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, no off-the-shelf models can be used (without further development by EPA) for benefit-cost analysis of health effects associated with air regulation except for the EMPAX-CGE model used by EPA for the "prospective" study of Clean Air Act regulations (US EPA 2011, Chapter 8); the EMPAX-CGE model incorporates some but not all of the features described above. Modifying an existing model written in a flexible programming language would take a matter of weeks, however, it would take a substantial research effort to obtain data to estimate or calibrate the relevant valuations and elasticities, and choose nesting structures and functional forms for equations in the CGE model to represent substitution and complementarity relationships (for nonseparable goods) or control technologies.

The following sequence of models represents 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. The VSL 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, and 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.

An interesting implication is 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 GE model will produce lower values for the mitigating activities related to the health effects of pollution but produces greater welfare benefits (due to both increases in H and decreases in M) than would be predicted by 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.

There are currently no "off-the-shelf" CGE models for use in benefit-cost analysis that contain Model 3's representation of the implications of air quality regulations for health outcomes. The closest model would be the work previously discussed for analysis of the GE 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, it would be possible to construct small aggregate models that include rough parameters for the connections among pollution, healthcare and health outcomes. Such models could provide insight into the kinds of results on effects that more extensive research and more careful parameterization would produce, and would possibly even provide some insights regarding the magnitude of the estimated effects.

Further issues to be considered are associated with the amenity effects of air pollution that have been estimated with hedonic models. A hedonic model is a reduced form description of what the market equilibrium implies a household would pay for reduced air pollution at a given residential location. Because it is not a structural approach, hedonic analysis does not isolate the causes (e.g., health concerns or visibility) for a household's willingness to pay more for these improvements. For example, 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. To do so would require that assumptions be added to describe how the hedonic result should be linked to preferences. 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?*

Research on contingent valuation (CV) asks respondents questions designed to elicit their WTP to improve some aspect of environmental quality.[35] This literature may be useful but 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 sources of data and information can be found in the quasi-experimental literature in which regulation is treated as an external effect on behavior that is linked to environmental quality.

Claims have been made that regulations with 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.[36] 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 GE 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 economic 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. With 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,

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[35] See Carson (2011) for a bibliography of CV studies.

[36] These connections have several aspects. 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.”

Hafstead and Williams (2016) for an environmental CGE model that incorporates 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, some empirical estimates of the observed relationship would be needed.

If CGE models themselves could be formulated that produced some form of 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 health effects

> *Charge Question: What approaches could be used to incorporate these additional effects? What are the conceptual and technical challenges to incorporating them? Under what circumstances would the expected effects be too small to noticeably affect the quantitative results?*

Introducing indirect health effects into CGE models is straightforward in theory and quite difficult in practice. It requires developing and parameterizing a health production function of the type discussed in Section 4.5.1. The principle challenge will be to obtain adequate data on all inputs (including non-marketed activities) needed to estimate the parameters of the function. For example, some actions that an individual might take to address environmental risks, including weight loss, exercise, and appropriate medication, will have indirect effects on health because they will cause changes beyond a simple decrease in the probability of death. Furthermore, time and resources would need to be allocated to these activities and treatments. Measuring how individuals trade off all of these inputs, and determining the consequent impact on health, requires highly detailed data that will be difficult to obtain for large populations.

As discussed below in Section 4.6, one of the potential indirect links between regulation and health that is often discussed—unemployment—is not sufficiently well understood for it to be introduced into a GE model at this time. Other indirect links are likely to be even more difficult to implement and, absent compelling statistical evidence to the contrary, smaller in magnitude. EPA could consider improving models of health production to be a long term research task but the SAB recommends against attempting to include indirect impacts of regulation on health in the near term.

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 unemployment. Very few CGE models capture unemployment and long-term joblessness, so addressing 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 these effects 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

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 the insured. 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 was 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 were forecast to have a single insurer serving every county, with 18% of eligible consumers served by a single carrier (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 reductions in air pollution 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.

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 costs for medical care, these individuals could experience changes in relative preferences as a result of air pollution control-mediated improvements in health status. Expressed 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. A recent survey of the literature on health state-dependent utility (US EPA, 2015b), notes 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 changes in preference 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, no *a priori* reason suggests 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 relevance here. 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 EPA's Second Prospective study of the costs and benefits of the Clean Air Act Amendments under Section 812 of the Clean Air Act (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 Second Prospective report, also called the "812 study" because it was required by Section 812 of the Clean Air Act, 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 a rigorous pre-dissemination information quality review, but the Second Prospective study and the Council's reports suggest that no such review was performed.

For these reasons, a preliminary step should be taken before applying the 812 approach: conduct a rigorous and transparent evaluation of information quality and the validity of the model's assumptions about cost savings passed through to consumers. Taking steps beyond such an evaluation 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 does not provide 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.

Little empirical work 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 significant welfare benefits 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 or costs to productivity from air pollution, although potentially very important, are clearly more tenuous in nature. 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)?*

As discussed below, research does indeed support development of these techniques for goods with *use* values. However, the SAB considers efforts to incorporate *non-use* values into GE models to be undesirable. By definition, non-use values produce little or no impact on behavior and thus they would be: (1) difficult to measure reliably; and (2) separable from other goods when added to household utility functions. Both characteristics mean that it would be a mistake to embed non-use values in a GE model: the numerical results would be difficult to defend, and integrating them into the model would produce little or no impact on other variables. If EPA wishes to consider non-use values, it would appropriate for that to be carried out as a separate PE calculation.[37]

However, integrating goods with use values would be an important and valuable step forward. The relevant literature is still in its early stages and the development of GE models suitable for regulatory use should be considered a long-term research activity rather than a task that could be accomplished immediately. A key task will be to incorporate non-market goods into utility or production functions without imposing separability between market and non-market demands. Doing so would provide valuable links between changes in environmental quality and demands for market goods, and it would also permit feedbacks from changes in market activities to levels of environmental quality (see also Section 6.2.1).

To introduce non-market goods into preferences or production functions, 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. One possible approach would be to follow the Perroni (1992) logic, in which calibration is based on the same basic approach used with purely market goods, but with the shares defined in terms of shares of virtual rather than actual expenditures, where virtual expenditures include the imputed values of non-market services. In these cases, virtual prices must be specified consistently with the mechanism linking the amount of the non-market 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.[38] Thus the process is understood and well vetted. Introducing measures of public goods, Q_1

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[37] As noted Section 4.10, for transparency and consistency PE estimates of benefits should usually be reported separately from GE estimates rather than summing the two.

[38] 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

through Q_n (including but not limited to environmental quality), into a representative agent's utility function without imposing separability might look as follows, where G_s, G_c, and G_o indicate sets of market goods that are substitutes, complements, or neither for public goods, and L is leisure time:

$$U(G_s, G_c, G_o, L, Q_1, \dots, Q_n)$$

Because the function does not impose separability, an increase in the provision of public good Q_i, other things equal, could be expected to lead to changes in market demands: an increase in demand for G_c and a decrease in demand for G_s. In contrast, an approach that imposed separability might use a utility function defined as follows, where U_m is utility from market goods and U_{nm} is utility from public (non-marketed) goods.

$$U_m(G_s, G_c, G_o, L) + U_{nm}(Q_1, \dots, Q_n)$$

Under the separable specification, changes in Q_1 through Q_n can be shown to have no impact on the allocation of the agent's market spending on goods G_s through L except possibly through income effects associated with virtual income. This is clearly a more restrictive specification and it rules out behavior that could be important (for example, someone choosing more outdoor recreation when air quality improves).

Continuing with the discussion of the non-separable case, 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 public good Q_i) will be:

$$\pi_i = \frac{U_{Q_i}}{U_M}$$

where the subscripts designate partial derivatives with respect to $\mathrm{Q_i}$ and M. Let Q_{i0} be the baseline or initial level of Q_i, and let Q_{i1} be the new level, with $Q_{i1} > Q_{i0}$. Then, the following expression provides an approximate measure of the economic value of the improvement:

$$\pi_i \cdot (Q_{i1} - Q_{i0})$$

If a PE or other estimate is available for this value in the literature, the utility function can be calibrated to reproduce it by setting one of its parameters so that $\pi_i \cdot (Q_{i1} - Q_{i0})$ matches the PE value. This provides a parameterization method that can be used for non-market goods.

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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.

As a specific example, Espinosa and Smith (1995) described how non-market environmental services can be introduced into preferences through the threshold consumption parameters of a Stone-Geary specification. This strategy assumes 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, 1996) incorporated all the feedbacks and the emission process.

Finally, it should be noted that moving away from use of the separability assumption will take time and will present formidable obstacles. A fully general utility function would require estimates of cross elasticities between all pairs of inputs, including those that are not traded in markets. Appropriate data is not readily available for estimating all of those values. Moving away from separability will need to be done judiciously, identifying and focusing on the most important non-marketed goods first.

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. 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 impose the assumptions that agents take prices as given and that implicit entry and exit conditions yield zero profit outcomes for all producing sectors represented in the model.

When the benefits (or dis-benefits) attributable to 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 a further level of consistency needs 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 GE effects of major rules are important enough to warrant modifying benefit-cost estimates developed using PE 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 in order to gauge the GE price effects of the size of these cost impacts across sectors. In the context of industrial organization analyses of the extent of competition, residual demand models can be interpreted as GE demand analyses where the focus is on a few linked markets that are used 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 GE 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.

A broader question is 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 (i.e., unified river basins) and compare these results 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. First, aggregate the regional shocks and apply the aggregate shock at national level. Then compare 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 watersheds to airsheds, it remains to be determined whether a regional approach based on airsheds or on state-by-state disaggregation would be more useful, or whether the two approaches could be combined. The challenge is that states usually have multiple airsheds, while many airsheds span multiple states. California, for example, has several air quality management areas, some of which are delineated along the lines of airsheds (such as the South Coasts Air Quality Management District). EPA's 2011 Cross-State Air Pollution Rule, in contrast, involves a large airshed encompassing parts of many eastern states. In some cases, a state's contribution to its own air quality can be as low as 1% of the total pollutant loading. These different levels of aggregation would be challenging to align in a CGE model.

Another approach to the issue would be to use 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 defined 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 U.S. 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 that relate to health and other considerations. In addition, this approach can trace geographic interactions: results for the U.S. as a whole are not necessarily the simple sum of individually-calculated direct state 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

A few guiding principles should inform an evaluation of whether 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 sub-models.

Finally, a balance needs to be struck between capturing detail and complexity vs. 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. Methods to identify potential errors and to increase confidence in model results include providing clear explanations in heuristic terms about why economic impacts take the form they do, combined with sensitivity analyses that demonstrate that the model responds in theoretically correct and quantitatively reasonable ways to changed parameters.

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, the literature provides a standard set of techniques 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 to limit the modeled 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 many regulatory policies, a great deal of progress has been made in scaling multiregional CGE models down to the census region, state, and National Electric Reliability Region. Economy-wide models with such disaggregation include the USREP model (Rausch and Mowers, 2014), the DIEM-Electricity model (Ross, 2014), and the NERA NewEra model (Montgomery, et al. 2009).

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 primarily produced from coal. Thus, the mix of input fuels used by generators will dictate the cost of compliance and the incidence of cost impacts on energy prices. That is, areas in which power is produced by burning coal will likely show greater impacts, in contrast to other regions in which power is generated by hydro, renewables, natural gas or nuclear. 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 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 NAAQS attainment status of particular counties and metropolitan areas. Because failure to reach attainment results in more stringent emission reduction requirements (relative to counties in attainment), a new policy is likely to have spatial heterogeneity in the degree to which it will yield additional abatement, and thus in subsequent costs and tertiary effects on energy prices. Again, the point is that a judiciously chosen degree of spatial 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 judicious aggregation is required to minimize the first-order errors that would otherwise be induced by mismatching airsheds 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. Examples of CGE models that feature sector-level disaggregation are discussed in US EPA (2016a, 2016b). What comprises a sector is not 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 PE 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 GE 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 creates patterns of industry locations that are well known: the Rust Belt, the Corn Belt, and 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 because 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 predicted by the PE model (e.g., impacts disaggregated along a dimension such as: industry classification, production technique, region, or demographic group) 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 its geographic and sectoral composition. Here, aggregation focuses on income distribution. Analysis of impacts on 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 model result showing a 2% reduction in earned income. This is insufficiently detailed to adequately assess distributional impacts; whether such a reduction is 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. It is possible for CGE models to detect and report such heterogeneous effects (see, for example, Rausch and Reilly, 2011). However, the CGE model needs to be designed with this purpose in mind.

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 because such policy interventions that will impact exposure; 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 unemployment, the need to retrain laborers if human capital affected by an air regulation is particularly specialized, and the heterogeneity of transition costs across 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 associated with capital flows between sectors have long been included in CGE models using a variety of techniques, and are discussed in more detail in Section 5.5.2. 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 over the business cycle and according to policy design (i.e., whether the policy is a tax or an emissions standard). Labor market transition costs are discussed in more detail in Section 5.5.

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—e.g., 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 not 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, models have 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.[39]

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.[40] 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 can

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[39] The possibility of distinguishing labor skill categories in a CGE model is demonstrated in the analytical GE model of Fullerton and Monti (2013). They show how environmental regulation can raise the high-skill wage relative to the low-skill wage rate.

[40] 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.

provide endogenous information on two out of three of the drivers if labor or total factor productivity is endogenous (responding to prices and sometimes to explicit investment in research and development).

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 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 U.S. 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. CGE models with appropriate features can shed light on both competitiveness and leakage.

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).

Other recent approaches, such as Melitz (2003) offer the possibility of modeling heterogeneity of firms and their production technologies, both domestically and abroad, which potentially offers better alignment with the stylized facts about production technologies, emissions across firms, and export performance. Modeling firm heterogeneity is at the research frontier, but initial studies suggest that for carbon policy, at least, it can have a significant impact on predicted competitive effects and emissions leakage. Moreover, independent of trade impacts, the consideration of firm heterogeneity can clarify 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. Heterogeneity among firms arises in many places in the economy and, in the near term, EPA should keep apprised of the emerging literature. Over the longer term, it should consider moving the treatment of trade, in particular, beyond the assumptions of Armington substitution and perfect competition.

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).

In terms of understanding a regulation's impacts on competitiveness, one of the most important challenges is adequate 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 domestic changes to boiler regulation using a CGE framework, and determining the international trade implications would be even more difficult. 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 clearer, as are the implications for international trade in cement.

Another unresolved point about both competitiveness and 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).

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 SAB recommends CGE modeling as a key method for assessing international competitiveness effects and leakage. Some good commodity-specific PE trade models might also 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 multiple candidate structural formulations of the model 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 warranted.

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 also valid for an analysis of economic impacts. 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. 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 using CGE models for economic impact analysis are the same as the advantages and drawbacks of using these models for measuring social costs; these 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.

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: a full-employment 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, some impacts could, in principle, 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, assessments of labor market participation would require modeling the participation decision.

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 unemployment or underemployment (workers who want full-time jobs but can only work part-time jobs). Voluntary changes have very different implications than 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 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 to do so and to help evaluate the credibility of those methods in the environmental context. This assumption can be loosened in a variety of ways.

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 U.S., 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 assumption is easy to implement. And it could provide a reasonable representation of the short-run effects of policy at a time with 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 excess capacity means that supply constraints aren't binding. 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 approach can provide good short-term forecasts, but it does not allow unemployment to respond to policy changes. 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, because of substantial job turnovers). Also, 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.

That simple approach can be enhanced by explicitly modeling barriers to instantaneous adjustment. These are already widely used (though still far from ubiquitous) for modeling capital. Because capital stocks are often expected to last for many years and have long payback periods, regulations that require significant shifts in types of capital can create substantial transition costs. Methods used for modeling transitions 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), 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); and detailed engineering optimization models tracking process-level capital stocks in subsectors. Process-level or vintage capital models can be particularly useful in modeling the electric sector. It is relatively large in size; is capital intensive; has low substitution between inputs used with any given type of generator; has relatively clear rules for determining which generators are used (dispatching order); and is subject to a very wide range of air regulations.

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. The standards that must be met for modeling impacts are somewhat looser than those discussed in Section 3.7 for evaluating social costs. The key difference is whether the model includes the theoretical structure needed for calculating welfare changes: it is required for social cost calculations but may not be necessary for some assessments of impacts. Most of the approaches discussed below do not support welfare analysis and are therefore inappropriate for social cost calculations. However, they may be useful for assessing impacts as they are capable of analyzing the following aggregate and sectoral impact categories to various degrees at the national or regional levels: (1) gross output; (2) gross domestic product or value-added; (3) personal income, employment, tax revenue, investment; and (4) 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 assumption of linearity, absence of a role for prices and markets, absence of input substitution possibilities, lack of behavioral content, and assumed perfect elasticity of supply. 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).[41] However, while many empirical I-O models incorporate one or two of these advances, all of these advances 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). With that said, some CGE models do use input-output relationships in modeling firms' demands for intermediate inputs.

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). These efforts include the

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[41] 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.

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 data 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 remains about the legitimacy of this approach. First, it has been criticized as mimicking Say's Law (supply creates its own demand), though this is only a serious problem when a policy causes the economy to expand. Second, the demand- and supply-driven model parameters may not be mutually consistent (Oosterhaven, 1988; Miller and Blair, 2009).

5.6.2. Social accounting models

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. 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 full set of variables is first divided into a group of endogenous variables, whose behavior is the focus of the model, and a group of 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. The typical CGE approach has no comparable automatic humility. 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.[42]

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. 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

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[42] 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.

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. Moreover, the reduced-form econometric component of the models is subject to the Lucas critique.

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 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 (Abt, 2014). 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 GE, 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 a desirable 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). As discussed in Section 3.6, similar functionality could be achieved with CGE models by linking them to detailed PE sectoral models.

5.6.5. Dynamic Stochastic General Equilibrium Models

Dynamic stochastic GE (DSGE) models are closely related to CGE models. Both are economy-wide approaches, with factor endowments, representative agent(s) maximizing utility, 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 or can evolve over time. Thus, in principle, DSGE models share the desirable characteristics of CGE models for evaluation of welfare impacts of policies.

One respect in which DSGE models differ from most CGE models is that they include a financial sector and monetary authority. As a result, they introduce additional assumptions about the behavior of government: in particular, how the monetary authority reacts to inflation. Since DSGE models include money as an additional commodity, market equilibrium conditions determine prices uniquely[43] and the inflation rate is endogenous. A common rule for representing the monetary authority has it 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, at which point interest rates are increased and so on. Thus, the monetary policy rule generates a business cycle.

A second difference is that CGE models are typically deterministic, and agents within them treat current and future conditions as certain.[44] In contrast, DSGE models: (1) include random shocks to the parameters that determine market equilibrium outcomes; and (2) represent households, firms and government as making decisions under uncertainty (Sbordone, et al. 2010). DSGE models replace the CGE assumption of perfect foresight by the assumption, known as rational expectations, that agents correctly anticipate the probably distributions of future variables. 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 can be used as a tool for analysis of business cycles and how monetary policy affects the real economy and inflation.

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, 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. In addition, DSGE models would provide perspective on how implementation of regulations at different points of the business cycle might affect their overall costs and their consequences for inflation and unemployment.

The solution algorithms for DSGE models can be more complex than those for CGE models, and typically involve solving a first or second order Taylor series expansion around the steady state. This is a potential limitation, since regulatory analysis will generally be undertaken when the economy is not at a 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.[45]

Since DSGE models have the same microeconomic foundations as CGE models and include similar productivity variables, the costs of regulation could be introduced in similar ways. However, the DSGE formulation also allows explicit introduction of regulatory uncertainty. For

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

[44] 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 no complete contingent claims markets exist, for every commodity and possible state.

[45] See www.dynare.org.

example, 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 latter approach could provide a way to understand how uncertainty about future costs or about future changes in policy would affect current compliance decisions.

However, DSGE models have a significant drawback for use in regulatory analysis: they typically have far less sectoral and structural detail than CGE models in their treatment of industries and households. They also lack policy-specific externalities such as health effects on the benefit side, although as noted elsewhere that drawback is shared with most CGE models. This lack of detail means, for the near term, that DSGE models are not an alternative to CGE models for economy-wide analysis of air regulations. However, they could be used to augment CGE analysis by providing insight into the impacts of air regulations on unemployment, transition costs, and inflation. In addition, they would be a valuable tool for exploring the impact of regulatory uncertainty on aggregate investment and business behavior.

5.6.6. Summary

No single model is best 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 appropriate application of the former two modeling approaches would be to cases of very short-run impacts of a relatively small nature, where substitution possibilities are limited and price effects are 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 the limitations of the component modeling approaches.

Overall, any modeling approach or individual model to be used by EPA in the future should be carefully vetted. This need for vetting includes models typically used at the regional level that are applicable to the national level and vice versa. If failings are identified, decisions 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 COMPARABILITY BETWEEN RESULTS

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,[46] comprehensive coverage of all potential market effects in a way that supports identification of unintended consequences,[47] explicit recognition of finite resource endowments that account for the opportunity costs of lost work hours or labor and capital diverted to pollution control activities, requirements that all markets clear, and the requirement 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.

CGE modeling is most valuable when evaluating a new regulation involving an out-of-sample inference; that is, when the analysis is out of the realm of historical policies. It is in these circumstances that CGE models can provide the greatest insights since straightforward policy evaluation tools from statistics cannot be applied. However, complexity and data requirements are a significant challenge. An analysis should use a transparent CGE model built on microeconomic foundations and as simple as possible given the analytical task at hand. The interpretation of results, and the understanding of the model by outsiders, becomes more difficult as additional features are added to the model.

PE models can be just as rigorous as GE models and often play a critical role in policy analysis. But if PE models are used inappropriately, then key spillovers can be missed. One example involves the assessment of the land use impacts of biofuels expansion. Studies that only considered the corn ethanol-gasoline pathway overstated the impact of ethanol expansion on total

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[46] Examples are positive employment effects of required investment in pollution control equipment and negative employment effects of reduced coal use on coal mining.

[47] Examples are rebound, or Jevons' effects, associated with reduced prices for transportation fuels or lower driving cost caused by CAFE standards.

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 approach is particularly common in the case of household modeling using survey data. Often, rather than imbed the disaggregated households into the CGE model itself, prices, wages, and other information from the CGE model are fed into a simple model of household welfare allowing for determination of the differential incidence of a policy (Hertel, et al., 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 a CGE model ensures that 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 the model fully accounts for all taxes, subsidies, profits, and other flows of income and expenditure. 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. Potential pitfalls in geographic or sectoral aggregation need to be addressed in each case, particularly for pollutants where the spatial distribution varies, where atmospheric processes are complex, 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, some standard checks can be applied. For example, any well-specified CGE model should be homogeneous, which means that a 10% shock to the numeraire results in a 10% rise in all prices and incomes, but no change in the quantities predicted by the model. Further, verification that Walras' Law holds in the model is a check on internal consistency, not only of the model's theory, but also of its coding and its use 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, et al., 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 non-market 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 represent 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 non-market 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.

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 step would allow the model to determine market effects of air quality, changes in the marginal value of medical care as health improves due to improved air quality, and health improvements (e.g., changes in purchases of other goods as medical expenditures fall). It would also 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 address the "co-benefits problem," which arises when multiple regulations have impacts on a single pollutant.[48]

In the near term it may be useful to introduce non-market use values through an approximation that does not fully account for non-separability between environmental and market goods. 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. Such an approach would capture first-order impacts of air quality changes on welfare but would necessarily miss second-order impacts that would arise if substitution or complementarity between environmental quality and market goods were taken into account.

Even a rudimentary effort to model non-separable benefits in a CGE framework has benefits:

- Including an income constraint on willingness to pay for non-market 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*

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[48] To illustrate the co-benefits problem, suppose that two unrelated regulations are being considered. Regulation 1 would reduce a pollutant by 10 ppb relative to baseline and regulation 2 would reduce it by 5 ppb relative to baseline. Evaluating the regulations separately would credit them with 15 ppb of reduction if both were imposed. In practice, however, the impacts may not be additive the total reduction could be smaller.

> *implications of compliance costs when there is not a corresponding capability to incorporate benefits?*

Much can be gained from improving the treatment of environmental benefits in GE models, and two key issues will be discussed further below. Over the long run, the SAB recommends placing high priority on this area of research. With that said, imperfect measurement of benefits does not justify failing to use existing GE models when they are available and can shed light on social costs and economic impacts. Evaluating the patterns of benefits and costs that a regulation distributes throughout the economy can be challenging, as is the task of integrating that information into an overall welfare measure. However, these challenges are already present under EPA's current PE methodology and are not exacerbated by adding GE analysis, even when measures of benefits are incomplete. The main challenge is rhetorical rather than analytical: with current GE models EPA must emphasize that the GE results alone are not a complete analysis of a regulation's impact and cannot be used in isolation.

6.2.1. Improving the treatment of benefits

With existing GE models, net measures of welfare are usually computed by first calculating GE measures of costs and the benefits that can be calculated within the model, such as changes in time endowments and the use of medical care, and then tacking on PE measures of all other benefits. Most of the PE measures are for goods that are not bought or sold in markets, so it will be convenient to refer to them as non-market benefits. Formally, this approach imposes the assumption that the non-market benefits are separable from market goods when they enter utility or production functions: that is, it assumes that changes in those benefits have no impacts on behavior or market demands. Moreover, a consequence of separability is that changes in non-market benefits will cause no feedback effects on environmental quality itself.

Although this approach is tractable, the assumption of separability is rarely tested and is clearly too strong in some cases. The alternative, non-separability in preferences or in production relationships, would generate important feedback effects inside and outside markets. These feedbacks could even affect social costs by changing relative prices. As a result, research on relaxing the separability assumption for non-market benefits is important on two levels: (1) improving GE measures of benefits, and (2) capturing indirect impacts on costs.

The central point of existing GE research on non-market goods is that both market outcomes and non-market outcomes are jointly determined, and hence non-separable. As noted by Carbone and Smith (2008), the social accounting matrices (SAMs) on which most CGE models are based omit non-market interactions with environmental systems that can create important feedbacks. As a result, SAMs lead to model structures that omit those feedbacks and effectively treat them as negligible. However, revealed preference non-market valuation methods (e.g., hedonic property value, or travel cost) have been used to measure such feedbacks for over 50 years. Those methods are all based explicitly on the existence of links—or non-separability—between non-market values and observable market behavior (including the use of leisure time).

Similarly, an extensive literature demonstrates feedbacks between non-market goods and averting behavior by individuals—another manifestation of non-separability. Moreover, those actions can change the non-market good itself. For example, individuals can undertake averting actions to reduce their exposure to air pollution. These actions may raise GDP but can have unintended effects that reduce welfare by contributing to everyone else's exposure to air pollution. Instead of walking or biking, for example, a person could drive her car to protect herself from the polluted air (Kahn and Zheng, 2016).

These literatures imply that separability is inappropriate for many non-market goods. In practice, however, the importance of relaxing separability will depend on the mix of non-market goods being enhanced and on the magnitudes of those enhancements; hence the need for additional research. A particularly important area where work is needed is to understand the behavioral consequences of the large benefits implied by WTP assessments of risk reductions: the magnitude of those benefits is sufficiently large relative to household income that assuming they cause no behavioral impact, as is the case with separability, is hard to justify. To date, few studies analyze the implications of GE 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?)*

As discussed Section 3.5, theory strongly justifies using an absolute measure, equivalent variation (EV), to assess the impact of a policy. This is particularly important when health or other external benefits are not included in the analysis, as an absolute welfare measure can be compared, albeit in a not entirely consistent way, with independent estimates of benefits. For clarity in communication, it is important that EVs (and other measures used for evaluation) also be expressed as a percentage of baseline income or wealth so that all users of the analysis understand the scale of impacts. Thus, presenting absolute and percentage changes are not alternatives; rather, presenting both would be the best practice. Absolute changes are also most useful when comparing results from separate PE and GE analyses, although it is important that both types of analysis use the same baseline scenario. Moreover, when EVs from both PE and GE models are available, comparing the results would help identify the magnitude and nature of the most important GE impacts. Finally, absolute changes may be most convenient for comparing predicted impacts from regulation with actual outcomes *ex post*.

Both the absolute welfare changes and the relative ranking of policies may vary with different baseline scenarios. In order to assess the confidence to be placed in relative welfare rankings or absolute welfare impacts, it is important to examine scenarios with different baselines as well as with different parameters that drive economic responses. This is true no matter whether a PE or GE model is used.

In general, the most useful information to be derived from a GE analysis is the ranking of policies in welfare terms rather than the precise quantitative comparison. That is, given the inherent uncertainties in a model, an analyst will usually be able to say that policy A is better than policy B with more confidence than she could say *how much* policy A is better. Moreover, sound theoretical reasons may lead her to expect one policy to provide greater benefits than another, and the rankings of policies from the model can be subjected to this test.

To clarify a point that seems implicit but unstated in the question, GE models are more appropriate for measuring *changes* in welfare from one scenario to another (as described above) than they are for measuring the *level* of welfare in a single scenario. All behavioral equations in GE models have residuals when they are estimated, and those residuals are generally absent from the model or are set to zero in simulations. The output of a GE model is thus a set of mean values rather than point forecasts. As a result, the models are appropriate for examining differences in those means, but not for providing forecasts of actual values of variables in specific years.

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?*

Presenting both PE and GE measures has clear advantages, but comparisons of the two have three 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 documented in the EPA White Papers (US EPA 2015a to 2015d and 2016a to 2016c), such a framework has not been developed and evaluated in the published literature.

The second limitation 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 (see Section 6.2.1). This assessment must consider specifically the implied market and non-market interactions and their implications for the model's characterization of feedbacks in its GE solution.

The third limitation relates to a more practical consideration. While few debate what constitutes a GE analysis, the boundary conditions for a PE analysis are not well-defined, as they require making a determination of what activities and prices are deemed exogenous to the policy.

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)?*

Two issues need to be addressed. The first is the use of proprietary models. To be clear, we take proprietary models to be those that meet the definition set forth by the NRC Committee on Models in the Regulatory Decision Process (NRC 2007). It defines a model as “proprietary” if any component of the model other than general purpose software (such as Excel or MATLAB) 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 unlikely that the sacrifice in transparency, including the inability for qualified third parties to reproduce results, will 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 both to understand and to 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), while 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 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. Sensitivity analysis is also essential. When possible, the results of alternative models could be provided, 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 these approaches to understand the implications of results and their limitations for policy decisions.

A public vetting of the models may be helpful for aiding public understanding and engaging qualified third parties in model validation. This vetting could take a number of forms. In the short run, a useful step would be studies of particular policies along the lines of those carried out by the Stanford Energy Modeling Forum.[49] In the longer term, additional options could be considered including: (1) public posting of model code, data and parameters (as discussed elsewhere in this report), including a mechanism for accepting comments from qualified members of the public; or (2) comparisons of models over specific historical periods given specific sets of policy shocks (similar to exercises undertaken with climate models).

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 the experts have more confidence in those estimates than is the case.

Moreover, a well-known result called Jensen's Inequality in mathematics, and the "Flaw of Averages" in more recent literature (Savage, 2009), 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 GE 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

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[49] The Stanford Energy Modeling Forum (EMF) is a research effort at Stanford University that brings together leading experts and decision makers from government, industry, university and other research organizations to study energy and environmental issues. EMF seeks to harness the collective capabilities of multiple models to improve our understanding of how these systems work. See https://emf.stanford.edu/.

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 ambiguity is much more difficult to treat in a formal quantitative fashion for most CGE models.[50] A typical CGE model offers a description of hypothetical data sets given some assumptions about parameters, like supply and demand elasticities. One standard method of calibration assigns plausible values to these parameters based on empirical estimates taken from the literature. Since models calibrated in this way are not constructed to explain any actual data sets, they come with no measures of model accuracy like an R^2 for an econometric model. Accordingly, no method is available to say which of several such models is the most accurate, nor to describe the model uncertainty. One can wisely conduct a sensitivity analysis that describes how sensitive conclusions are to choice of model as well as the within-model sensitivity analysis that perturbs the model parameters, but it cannot be concluded within a typical CGE framework that one model is more accurate than another.[51] This is a serious shortcoming of this intellectual tradition that can be remedied only if the models can either be enlarged to the point that they can be treated as hypothetical descriptions of actual observable data, or data sets can be found that are so dominated by the forces described by the models that no enlargement seems necessary. In either of these circumstances, a horse race can be run to see which one is most accurate. (One of the critical enlargements of the model would be left-out, e.g., unobservables like the residual terms in econometric equations. It is the stochastic properties of these unobservables that fundamentally determine the measures of goodness-of-fit.)

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

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[50] See Pindyck (2013) for an illustration of the importance of model ambiguity in the context of integrated assessment models used in developing measures of the social cost of carbon.

[51] This applies to the typical practice used to parameterize CGE models, but it is not an inherent limitation of the methodology. Some CGE models have been built using full econometric estimation and could be subjected to econometric goodness-of-fit tests. One example is described in Jorgenson and Wilcoxen (1990) and Jorgenson, et al. (2013).

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 analysis is 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. Rather than for comparing different models, however, it is primarily useful for comparing alternative variations in the same model (e.g., change in spatial or temporal resolution, inclusion of a specific process).

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 (see Section 6.3.1).

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 not to 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. Given sufficient funding support and time, one could imagine performing 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 ambiguity as represented by the models included. While an actual study of this type is likely not feasible, it is a useful concept for thinking about differences between models.

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 is 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 is 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. 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 the decision is about 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 that it can identify areas in which the value of new information or methods is large. Changes in some parameters may 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 that are most important.

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 of the probability distribution 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 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.

Improving data availability

Because access to high-quality data is a key obstacle to high-quality CGE modeling, we recommend that EPA collaborate with outside organizations and researchers to establish an 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 and their use and acceptance by stakeholders (including states agencies). In addition, as discussed in several places in the report, regulatory requirements for data quality are stringent and would be best achieved through a collaborative, open-source approach.[52] Building such datasets is resource-intensive and time-consuming to do well, so this should be regarded as an iterative task to be completed over time with contributions made by EPA and nongovernmental entities. While the professional payoff to academic researchers from building high-quality publicly-available datasets may not be great today, EPA is well positioned to provide rewards that universities could recognize.

If possible, EPA and its collaborators should draw on the experience of the Center for Global Trade Analysis at Purdue University, which has many years of experience producing an

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[52] Open source does imply the absence of oversight or quality control on the data. A robust mechanism for vetting and approving updates to the dataset would be required.

international dataset under the auspices of the Global Trade Analysis Project (GTAP).[53] Although GTAP itself is not open-source and focuses more on international agricultural trade than domestic environmental policy, it involves very wide collaboration and the experience of building and managing it would provide valuable lessons for designing a similar collaboration for environmentally-focused U.S. data.

In terms of populating an initial version the dataset, a possible starting point would be to develop a base dataset with modest sectoral detail but with consistent historical data for a number of prior years. A second task could be to refine the data for the electric power sector, since it is critical for many air regulations and detailed data can be obtained from the Energy Information Administration on the vintage, location, and emissions characteristics of all major generating units in the country. Over time, the dataset could be refined further to provide greater detail on other energy sectors, as well as to include greater regional and demographic detail.

Improving modeling of labor markets

For wider use of economy-wide models to evaluate air regulations, we also recommend that EPA encourage further development of CGE models that can capture 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 magnify 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). Thus, 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, particularly at the regional level.

Improving modeling of environmental benefits

A third recommendation is for EPA to encourage model developers to improve the treatment of environmental benefits in CGE models. One route is 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.

Another valuable step is to extend and enhance the treatment of non-market benefits into economy-wide models. As discussed throughout the report, and in Section 4 in particular, benefits are captured far less well in CGE models than costs. In large part, the difference is due to data availability: although much work has been done estimating non-market benefits in particular locations and situations, no comprehensive national-level datasets are available. Work on improving the treatment of benefits could begin immediately. As noted throughout the discussion of benefits in the report, a particularly important aspect of this research agenda is to move away from the current conventional practice of imposing separability between non-market benefits and goods and services that are involved in market decisions. Some improvements might

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[53] https://www.gtap.agecon.purdue.edu/

be possible in the near term, but, particularly due to data limitations, it should be considered a long term research project. Considerable time and resources will be required before CGE models with extensive treatment of non-market benefits will be ready for routine use in regulatory analysis.

Rigorous analysis of inconsistencies arising when linking models

Finally, we also recommend that EPA encourage research on the inconsistencies that arise when linking relatively aggregate economy-wide models to more detailed models of households, industries or regions. As noted throughout the report, tensions will always arise 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 other impacts of any given air regulation (which is often relatively high). As a result, it will often be very useful to link models such as: (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 (to understand 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 (which has a long literature in energy modeling and elsewhere) but rather on understanding the inconsistencies that arise from linked rather than fully integrated models.

Additional areas for research

To improve the transparency and public understanding of CGE analysis of air regulations, it would be useful for EPA to encourage a series of independent model comparison exercises like those carried out under the auspices of the Stanford Energy Modeling Forum (EMF) for energy models. One analysis that would be possible now is a comparison of open economy models 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. They 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 is to identify when each type of model is most appropriate.

A second model comparison exercise possible now is an assessment of the importance of fiscal and trade deficit closure rules. The literature establishes that both are important for understanding the GDP and welfare impacts of a regulation but is less clear about 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. A third comparison could focus on differences between models in the distribution of welfare impacts they produce across different socioeconomic groups.

Finally, an additional research task over the long run is to improve the modeling 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. This approach ignores variability across sources even though that variability may be a key consideration or policy makers.

In addition, perfect competition may be a reasonable economy-wide modeling assumption in the long run, but key sectors may be oligopolistic and perfect competition does not properly characterize regulated industries generally. Social costs and regulatory impacts may be significantly affected by regulatory constraints and sectoral concentration. More work in this area would be valuable.

7. GLOSSARY OF TERMS

Note: definitions below ending with (EPA 2015d) have been reproduced verbatim from the indicated source.

Adjustment costs: Costs incurred when installing new capital or hiring new workers. Adjustment costs are generally above and beyond the purchase price of the capital goods or wages of the new workers. Models that include adjustment costs generally assume that they vary with the rate of growth of capital or labor: that is, that firms in effect pay a premium for growing rapidly.

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 $Y = \beta X + \gamma$, then 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: Favorable effects society gains due to a policy or action. Economists define benefits by focusing on changes in individual well-being (i.e., welfare or utility). Willingness to pay (WTP) is the preferred measure of these changes as it theoretically provides a full accounting of individual preferences across trade-offs between income and the favorable effects. (EPA 2015d)

Capital deepening: An increase in the quantity or quality of capital used in production per worker. Capital deepening is one mechanism by which economic productivity grows over time.

Certainty equivalent: A certain payment that an individual regards as exactly as good as a given gamble prior to the gamble's outcome being known.

Compliance costs: Costs firms incur to reduce or prevent pollution to comply with the regulation; the two main components are capital costs and operating costs. Capital costs are often one-time costs related to the installation or retrofit of structures or equipment to reduce emissions; operating costs are reoccurring annual expenditures associated with the operation and maintenance of the equipment. (EPA 2015d)

Compensating variation (CV): A hypothetical transfer of income or wealth to an individual impacted by a policy that would leave the individual just as well off after the transfer as they were before the policy was implemented. See also equivalent variation.

Distortion: An economic factor that prevents a market from reaching the level of output that would maximize social welfare is known as a distortion. Examples of distortions include (depending on specific circumstances): taxes, subsidies, regulations, market power, price controls, asymmetric information, and positive or negative externalities.

Equivalent variation (EV): A hypothetical transfer of income or wealth to an individual in lieu of a policy that would leave the individual just as well off after the transfer as they would have been had the policy been implemented. See also compensating variation.

Foresight: The ability of an agent to anticipate the future consequences of a policy, as well as to anticipate future changes in the policy itself. Foresight arises when one or more agents in a model have goals or objectives that depend in part on future conditions.

Frictional unemployment: Temporary unemployment that occurs when an employee who has left or lost a job is searching for a new job.

Full employment: A macroeconomic condition in which aggregate unemployment is as low as possible without triggering inflation. Unemployment is not zero at full employment because some degree of job turnover is normal in a healthy economy.

Full income: Monetary income augmented by the imputed value of leisure time. An extended version of full income would include the imputed value of environmental quality or other non-market goods as well.

General equilibrium (GE): An analysis that includes all markets in an economy.

Hard linkage: Two or more models that were originally independent but have been tightly linked into a single aggregate model.

Hedonic property value model: A statistical method that uses property values in different parts of a community to infer what buyers are willing to pay for non-market amenities such as air quality that are measurable and vary across the community.

Hedonic wage model: A statistical method that uses differences in market wages across occupations with different levels of on-the-job risk to assess how employees trade off risk against income.

Market clearing: A market is said to clear when the price of the good is such that supply and demand are equal. General equilibrium models search for sets of prices that cause most or all markets to clear simultaneously.

Non-market value: The imputed willingness to pay by individuals or groups for goods and services that are not traded in markets, such as environmental quality.

Non-separable: Goods A and B are not separable from good C if changes in the provision of C affect an individual's willingness to make tradeoffs between goods A and B. The literature on non-market valuation generally relies on non-separability. For example, hedonic property value models assume that property values, other spending, and air quality are non-separable. That is, that changes in air quality (good C) change an individual's willingness to trade off spending on property and other goods (goods A and B).

Non-use value: A non-market value associated with a good that an individual does not use or consume. Two key non-use values are "existence value", which is a willingness to pay to know that something (say a wilderness area) exists, and "option demand", which is a willingness to pay to preserve something that the individual might want to use in the future.

Partial equilibrium (PE): An analysis that includes only a subset of markets in an economy. Often partial equilibrium studies focus on a single narrowly-defined market.

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. *Excess precision* arises when precision is reported with more significant figures than justified.

Price stickiness: A price that adjusts slowly when market conditions change is said to be sticky. Most CGE models do not have price stickiness: after an economic shock, prices jump immediately to their new market-clearing values. When a sticky price is present, the corresponding market will generally not clear until the price evolves to its new equilibrium value. Models with sticky prices generally include an explicit model governing how the relevant prices evolve over time. For example, some CGE models assume that wages evolve slowly over time in response to prices and unemployment.

Primary factor: An input to production, such as labor, capital equipment, buildings or land, that is not used up in the production process. Inputs that are used up or transformed are known as intermediate goods.

Putty-clay model: A model in which new capital goods are general-purpose and adaptable to many uses prior to installation (putty) but once installed become specific to an industry or production process (clay). Putty-clay models essentially assume that capital goods cannot be moved out of a sector that is shrinking apart from allowing them to depreciate. Other types of model assume that capital goods remain flexible and could be transferred from a sector that is shrinking to one that is growing.

Representative agent: An agent who is taken to be typical of a large group. Economy-wide models use representative agents to model different types of households and firms.

Reproducibility: Information is reproducible when it can be substantially reproduced, subject to an acceptable degree of imprecision, by a qualified third party based on only disclosed initial information. The concept of reproducibility applies to all forms of information, including data, assumptions, models and results. With respect to analytic results, “capable of being substantially reproduced” means that 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 (OMB 2002).

Separability: Goods A and B are separable from good C if changes in the provision of C do not affect an individual’s willingness to make tradeoffs between goods A and B. Separability between market and non-market goods is often assumed in economic models.

Social costs: The total burden that a regulation will impose on the economy. It is defined as the sum of all opportunity costs incurred as a result of a regulation, where an opportunity cost is the value lost to society of all the goods and services that will not be produced and consumed in the presence of regulation as resources are reallocated towards pollution abatement. (EPA 2015d)

Soft linkage: Typically refers to the passing of information between existing top-down and bottom-up models that have been independently developed where the models stay completely separate. Information flows between models may be one-way or two-way, but is never completely integrated. (EPA 2015d)

Structural unemployment: Unemployment that results from major, long-term changes that sharply reduce the need for workers in particular occupations and industries. Employees who lose such jobs may not be able to find a similar job in the region.

Transition costs: Short term costs incurred only during the time period when the economy is still adjusting to a new equilibrium. (EPA 2015d)

Use value: A non-market value associated with a good or service that an individual actually uses. For example, an individual may be willing to pay for improved air quality near her home.

Value of a statistical life (VSL): A summary measure for the dollar value of small changes in random mortality risk experienced by a large number of people. For example, if 10,000 individuals are each willing to pay $500 for a reduction in mortality risk of 1/10,000, then the value of saving one statistical life equals $500 times 10,000. (EPA 2015d)

Vintage capital model: A model in which capital goods produced at different dates have different characteristics and are tracked independently. An example application is energy efficiency: if newer equipment is significantly more efficient than older capital—and if the two vintages tend to be clustered in different firms or industries—it can be useful to track the two stocks separately. Doing so would allow the model to capture the higher energy intensity of the sectors with older capital. Without vintaging, all industries would have, in effect, capital with a weighted average of the two efficiencies.

Willingness to accept (WTA): The absolute minimum a seller would accept in exchange for a good or service.

Willingness to pay (WTP): The absolute maximum a buyer would be willing to pay for a good or service.

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APPENDIX A: CHARGE TO THE SAB

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

MEMORANDUM

SUBJECT: Transmittal of Charge to the Science Advisory Board Advisory Panel on Economy-Wide Modeling of the Benefits and Costs of Environmental Regulation

FROM: Al McGartland /*signed*/
Director, National Center for Environmental Economics, Office of Policy

TO: Holly Stallworth
Designated Federal Office, Science Advisory Board Staff Office

DATE: February 26, 2015

Attached is EPA's charge to the Science Advisory Board (SAB) Advisory Panel on Economy- Wide Modeling of the Benefits and Costs of Environmental Regulation. We look forward to the Panel's meetings and discussions of the charge and are eager to receive feedback.

If you have any questions or need further information, please contact Ann Wolverton from OP's National Center for Environmental Economics (NCEE) at 202-566-2278.

cc: Joel Beauvais
Christopher Zarba
Alex Barron
Ann Wolverton

Draft Final Charge on the Role of Economy-Wide Modeling in U.S. EPA Analysis of Air Regulations

In accordance with Executive Orders 12866 and 13563, EPA evaluates the benefits, costs, and economic impacts of major air regulations to inform the policy process and the public of their potential economic effects. While cognizant of limited resources and data, EPA strives to rely on the best available science when estimating these economic effects using both benefit-cost analysis and economic impact analysis.

Air regulations considered by EPA vary widely with respect to the types of pollution addressed, sectoral and geographic scope, regulatory design, stringency, types of benefits and costs, and other dimensions. EPA considers these characteristics when gauging which analytic tools can be applied in a practical and analytically defensible way to estimate costs, benefits, and economic impacts within a particular regulatory context. For nearly all benefit-cost analyses conducted by EPA in support of air regulations, costs are estimated using detailed engineering or partial equilibrium sector models which are compared to benefits - also estimated using partial equilibrium models. EPA has evaluated, and will continue to evaluate, the appropriate role for economy-wide modeling in informing the regulatory process.

Peer reviewers of economy-wide models (e.g., ADAGE and IGEM) noted that, on balance, these models provide useful information to EPA when evaluating climate policies. The Advisory Council on Clean Air Compliance Analysis review of the Second Prospective Study of the Clean Air Act Amendments stated that inclusion of benefits in the economy-wide model specifically adapted for use in that study "represent[ed] a significant step forward in benefit-cost analysis" but recommended that EPA be clear about which effects are, and are not, included in the CGE model. EPA recognizes that serious technical challenges remain when attempting to evaluate the benefits and costs of a specific air regulation using economy-wide models.[1]

Policy makers and the public also have a keen interest in the distribution of costs and benefits across households and sectors (i.e., economic impacts) through mechanisms such as energy prices or labor markets. Some external entities have conducted analyses employing economy-wide models to evaluate the distribution of costs of regulation. The accuracy and defensibility of such analyses is also dependent on the quality of the assumptions and data used to represent regulations in the model, and on inherent strengths and weaknesses of the model employed. Whether economy-wide modeling can provide more complete and better information than partial equilibrium and engineering models alone on the benefits, costs and other economic impacts (e.g., productivity, labor market outcomes) needs to be examined.

We ask the Panel to examine the technical merits and challenges, and potential value added of economy-wide modeling to evaluate social costs, benefits, and/or economic impacts of air regulations as a supplement to partial equilibrium or engineering approaches; advise the Agency of the results of this examination so that future EPA decisions on the use of economy-wide models are more fully informed;

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[1] EPA Advisory Council on Clean Air Compliance Analysis (2010). *Review of the Final Integrated Report for the Second Section 812 Prospective Study of the Benefits and Costs of the Clean Air Act*, EPA-COUNCIL-11-001.

and identify potential paths forward for improvements in economy-wide models that could address existing limitations and increase their potential utility as analytic tools to support regulatory decisions.

Technical merits and challenges in the use of economy-wide models to evaluate the social costs of an air regulation

When examining the value of a proposed government policy, the social costs can be compared with the social benefits in a benefit-cost analysis, or compared with the social costs of alternative policies that achieve similar goals in a cost effectiveness analysis. Computable general equilibrium (CGE) models provide one potential tool for estimation of the social costs of a policy.

1. 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. Given this context, 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?

2. 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.

    - Relative magnitude of the abatement costs of the rule.
    - Time horizon for implementation of the rule.
    - Number and types of sector(s) directly and/or indirectly affected by the regulation, and the magnitude of these potential market effects.
    - Level of detail needed to accurately represent the costs of the rule (e.g., 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?).
    - Appropriate degree of foresight (e.g., 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?).
    - How a model is closed, particularly how international trade is represented (e.g. When is a detailed representation of the rest of the world important for estimates of social costs?).
    - Considerations relevant to 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).

    - Ability to incorporate and appropriately characterize uncertainty in key parameters and inputs (e.g., engineering costs).

3. 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?

4. 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?

5. 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?

6. 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 affect other sectors of the economy. In some cases, modelers strive to integrate these two modeling 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?

7. 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?

Technical merits and challenges of using economy-wide models to consider the benefits of an air regulation

Analyses of the economy-wide effects of environmental regulations have largely been limited to an assessment of market-based activities, while ignoring that the demand for environmental quality also may respond to relative price changes. The Second Prospective Analysis of the Clean Air Act Amendments (also known as the Section 812 study) modeled the macroeconomic impacts of air quality-related health improvements by focusing on three specific effects: (1) the change in household time endowment from pollution-related mortality impacts, (2) the change in household time endowment from pollution-related morbidity, and (3) the change in medical expenditures associated with pollution-related morbidity.[2] This is an incomplete list of potential benefits. Some also have posited that there are potential health consequences of regulation, outside of those directly associated with pollution, that are not adequately captured (e.g., due to changes in an individual's employment status, or energy and food price increases that crowd out other consumption for lower income households). EPA seeks guidance regarding the incorporation of these potential benefits estimates into economy-wide modeling frameworks.

1. 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?

2. 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?

3. 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?

4. 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?

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[2] U.S. EPA (2011). *The Benefits and Costs of the Clean Air Act from 1990 to 2020*. http://www.epa.gov/air/sect812/feb11/fullreport_rev_a.pdf.

5. 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. Is there sufficient empirical research to credibly support incorporating other representations of mortality and morbidity impacts or additional benefit or dis- benefit categories? Is there an empirical literature to support the incorporation of potential health consequences of regulation, outside of those directly associated with pollution? What approaches could be used to incorporate these additional effects? What are the conceptual and technical challenges to incorporating them? Under what circumstances would the expected effects be too small to noticeably affect the quantitative results?

6. The public health economics literature examines how shifts in employment result in changes in health status and crime rates. Can these changes form 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?

7. 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? Under what circumstances would the expected effect be too small to be of importance to the quantitative results? 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?

8. 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?

9. 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)?

10. 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?

11. 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?

Technical merits and challenges in the use economy-wide models to inform economic impacts analysis for an air regulation

EPA has available to it a range of methods and tools already in use to evaluate the way in which positive and negative economic impacts associated with an air regulation are distributed (e.g., across sectors, households, and time) in accordance with a variety of Executive Orders (i.e., 12866, 13563, and others). Because CGE models capture interactions between economic sectors they may prove useful for identifying impacts outside of the directly regulated sector.

1. 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:

    - Short and long run implications of energy prices for households and firms.
    - Sectoral impacts (including price and quantity changes, plant openings and closures).
    - Impacts on income distribution.
    - Transition costs in capital or labor markets (e.g. representation of rigidities in the labor and capital markets).
    - Equilibrium impacts on labor productivity, supply or demand (e.g. labor market outcomes).

2. 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 have comparable policies, negatively affecting the international competitiveness of energy-intensive trade-exposed industries and cause "emissions leakage" that compromises the environmental effectiveness of domestic policy. 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? Does accounting for international competitiveness or emission leakage effects in a CGE model necessitate compromises in other modeling dimensions that may be important when evaluating the economic effects of air regulations? Are there other promising general equilibrium models or methods to assess international competitiveness effects of regulations?

3. 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? 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? 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?

4. 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?

5. Are there ways to credibly loosen the full employment assumption to evaluate policy actions during recessions? 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?

6. 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?

Considerations for generating directly comparable estimates of social costs, benefits, and economic impacts using economy-wide modeling

The benefit-cost framework as employed in EPA analyses compares the health and welfare benefits of a regulation with the social costs of compliance measures necessary to meet the standard. In light of the detailed discussions you have had – pursuant to the preceding charge questions – on representing social costs, benefits, and economic impacts in an economy-wide framework, please answer the following:

1. 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? What criteria could be used to choose between different economy-wide models/frameworks? What features are particularly desirable from a technical or scientific standpoint?
    - 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 whensocial costs are estimated using a CGE framework but some or all of the benefits are estimated using a partial equilibrium framework.
2. 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).[3] 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?
    - 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?)
    - What are the technical merits and limitations to presenting both general equilibrium and partial equilibrium measures when assessing the net benefits of a regulation?

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[3] In the Section 812 study, GDP was lower in the initial years of the analysis, but by the end of the reference period both GDP and welfare were higher with the Clean Air Act amendments than without them. See Exhibits 13 and 14 at http://www.epa.gov/oar/sect812/feb11/graphicsstack.pdf.

3. 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.”[4] 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? 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)?

4. 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.[5] Are certain types of uncertainty more of a concern when evaluating social costs, benefits, or economic impacts in an economy-wide framework?[6] Are challenges or limitations related to these uncertainties more of a concern than for partial equilibrium approaches to estimation?

    - 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)?
    - 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?
    - 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?

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[4] “This documentation should describe: The conceptual model and the theoretical basis …for the model; the techniques and procedures used to verify that the proprietary model is free from numerical problems or “bugs” and that it truly represents the conceptual model …; the process used to evaluate the model… and the basis for concluding that the model and its analytical results are of a quality sufficient to serve as the basis for a decision… to the extent practicable.” See http://www.epa.gov/crem/cremlib.html for more information.

[5] National Research Council (2013). *Environmental Decisions in the Face of Uncertainty.* Washington, DC: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=12568.

[6] For instance, several commenters noted that as air pollution is reduced to lower and lower levels, uncertainty regarding incremental mortality benefits increases.

    - How can the overall degree of uncertainty be characterized when reporting results from economy-wide models?[7]

5. 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?

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[7] Noting that cost estimation is also subject to great uncertainty, the National Academy of Sciences recommended in 2002 that EPA apply the same standards to assessing uncertainties in benefits. It recommended that EPA do more to identify uncertainties that have the greatest influence in estimates of public health benefits, as well as integrate these uncertainties into the primary analyses of benefits. Available at http://www.nap.edu/download.php?record_id=10511#.