Science Advisory Board (SAB) Economy-Wide Modeling Panel Draft Workgroup Responses to Charge Questions on Social Costs and Social Benefits to Assist Meeting Deliberations

-- Do Not Cite or Quote –

February 11, 2016

This draft is a work in progress, does not reflect consensus advice or recommendations, has not been reviewed or approved by the chartered SAB and does not represent EPA policy.

Contents

Cost Question 1 (C1)
Lead: Fullerton

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 describe advantages of other approaches. First, an engineering model can be particularly useful to analyze details of an environmental regulation, including particular constraints placed on the use of particular technologies. Firms may have multiple alternative production technologies available, and the engineering model can calculate the cost-minimizing combination of operations that meet both the regulatory constraints and production constraints. Given a particular set of input prices, these models can solve the optimization problem of the firm perfectly, while assuming no misinformation, no behavioral irrationality, and no feedback effects. The engineering model can then calculate the new breakeven price of output. A drawback is that engineering models can measure 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.

The second alternative is a partial equilibrium (PE) model that includes more economic behavior of both firms and consumers in a particular market. Instead of optimization over particular technologies, the 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. The PE model does not capture effects on other markets.

Those alternatives are frequently employed by EPA analysts who now contemplate more extensive use of computable general equilibrium (CGE) models. First-generation CGE models were often static 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 was used to calibrate production parameters, just as trade and other data was 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 alternatives such as: (1) labor-leisure choices by households, (2) econometric estimation of flexible production and demand systems, (3) recursive dynamic models with savings from one period used to augment capital in future periods, (4) perfect foresight dynamic models that calculate all prices in all periods simultaneously, (5) stochastic dynamic general equilibrium models, (6) noncompetitive behavior by firms, and (7) worldwide models of trade and factor flows between a dozen regions.

A possible disadvantage of the CGE approach is its relatively aggregated structure with less detail on each industry than offered by some engineering or partial equilibrium models. With additional programming resources, however, further model development has been undertaken to (8) 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 response C6.

New efforts are also underway to consider (9) involuntary unemployment and (10) apparently irrational behavior by consumers to explain why they don't make cost-efficient energy efficiency investments. Virtually any feature, such as (1) through (10), can be added with sufficient additional data, programming and computational resources.

Thus, we now face many differences *among* various CGE models, as well as differences among engineering models and partial equilibrium models. Some PE models are called "multi-market partial equilibrium" models, further blurring the distinction between PE and CGE models. And of course some very useful analytical general equilibrium models can be as simple as a PE model, while still capturing the important interactions and budget consistency of general equilibrium analysis.

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

All that said, a few key principles can guide the necessary choice between engineering models, PE models, and CGE models. Clearly an engineering or PE model may well be sufficient for analysis of a policy in one market that is not expected to affect other markets throughout the economy. 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:
   - 1A. 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
   - 1B. Significant distortions in those other markets (e.g. market power, taxes, or regulation).
2. A CGE model can provide a consistent and comprehensive accounting framework to analyze and to combine effects of a policy change on the cost side and the benefit side in a way that satisfies all budget and resource constraints simultaneously.
   - 2A. Especially in the case where improvements in environmental quality are not separable in utility but in fact affect demands for private goods which themselves may have welfare effects because of pre-existing market power, taxes, or regulation.
   - 2B. And even in the case where environmental quality public goods are separable in utility (and the interactive effects described in 2A do not arise), to take advantage of the consistent accounting framework where all costs and benefits are incorporated in one model, where an equilibrium satisfies all constraints.

We now turn to further discussion of these points. The best way to see the advantage of a CGE model described in the first point is to look at a simple expression derived from the analytical general equilibrium model of Arnold Harberger (Harberger, 1964), written before any CGE models were developed. He assumes constant marginal costs and linear demands (most valid for small changes). He thus calculates approximate changes in consumer surplus, while new-generation CGE models can calculate "exact" utility-based measures like an equivalent variation (see the answer to question C5 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:

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

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

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

The first term on the right-hand side of this expression is the direct effect on economic welfare from a change in tax or other price wedge in the *i* th market, as would be captured perfectly effectively by a partial equilibrium model of that market alone. It is the addition or subtraction from the "Harberger Triangle" welfare cost of that tax. The second term is the sum of all general equilibrium effects of T_i in *other* markets. Each such general equilibrium (GE) effect is zero or negligible if either (A) 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 if (B) 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.

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

The second point above is that a CGE model provides, in principle, a consistent and comprehensive accounting framework for adding up all the effects of a regulation including all costs and all benefits. However, we are concerned that the use of a CGE model that omits some of the costs or benefits may leave a misleading impression of net welfare effects due to incomplete accounting. Many of the benefits of air regulations are difficult to represent in a CGE model because of potentially non-separable ways that cleaner air may affect demands for private goods and services with pre-existing price wedges that affect welfare (the last term of the equation above). But leaving out those benefits entirely seems inappropriate; they could at least be modelled 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. 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.

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

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

This aspect of CGE models makes them difficult to validate using data on the aftermath of particular policy changes. The simulation of a policy change in a CGE model assumes no other changes, but any actual policy implementation is always accompanied by many other changes (in population, income, growth, technology, trade, macroeconomic shocks, or discovery of new natural resource deposits). The bottom line is that the simulation from a CGE model needs to be described carefully. It should not be said to "predict" nor to "forecast" the effects of a policy. It is a counterfactual calculation of effects only from the policy change and nothing more.

Cost Question 2 (C2)
Lead: Sue Wing

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, as paraphrased below.

- **i. the magnitude of the shock;**
- **ii. the time horizon of the shock;**
- **iii. the number and types of sectors impacted;**
- **iv. the details needed to represent the shock;**
- **v. the appropriate degree of foresight;**
- **vi. the closure assumptions about international trade;**
- **vii. the costs associated with model development; and**
- **viii. the ability to incorporate uncertainty.**

(i) The magnitude of the shock

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

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

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

(ii) The time horizon of the shock

The time horizon has little effect on the technical merit of using economy-wide or CGE models per se.

Econometric CGE models whose sectoral cost functions and household expenditure functions are empirically estimated on time-series data, and explicitly incorporate time as an argument, tend to be rare.

The vast majority of CGE models are numerically calibrated on the representation of the circular flow of the economy in a single benchmark year as represented by a social accounting matrix—a procedure which is inherently static. If implementation is a long way out from the benchmark year, it is always possible to approximate the economic conditions in the future period when the rule will come into force by scaling the benchmark factor endowment, adjusting the magnitude of the technical coefficients of the cost and expenditure functions to capture the effects of technological progress anticipated to occur in the interregnum, and solving the resulting model for a new synthetic static equilibrium. (The changes introduced by the analyst may draw on empirical estimates to a greater or lesser degree. At best they employ the same estimates generated by the aforementioned econometric CGE parameterization approach, but will tend to do so in a piecemeal fashion, concentrating on the dynamic components of input share equations.) Starting with the resulting future baseline characteristics of the economy, the rule can be imposed, and the concomitant changes in prices and quantities of commodities and factors, and welfare, evaluated.

This one-shot modeling approach fails to accurately capture the economic consequences of rules that are progressively phased in. The latter can be accommodated using a recursive dynamic modeling scheme in which the core static CGE model is embedded within a dynamic process that updates factor endowments and technology parameters in a myopic fashion. The important feature of this approach is the absence of forward-looking behavior: the updating procedure calculates the future values of dynamic variables using the values of prices and quantities in the current and perhaps past periods. (A good example of this principle is capital stock accumulation, which is simulated using a perpetual inventory equation in conjunction with a specification of investment as a function of current variables—e.g., an assumption that consumers exhibit a fixed marginal propensity to save out of their income, resulting in a multi-sector Solow-Swan model.) The trajectory of welfare impacts of the rule can then be computed based on the sequences of economic equilibria solved by the model under baseline economic assumptions and counterfactual policy assumptions. The bulk of CGE modeling studies that analyze the economic consequences of climate change regulation follow such an approach.

The biggest limitation of either the one-shot or recursive dynamic approaches is their inability to capture firms' and households' anticipatory behavior in advance of the rule entering into force. This gap is addressed by constructing intertemporal models in which the general equilibrium of the economy is formulated based on the first-order conditions to the problem of a forward-looking social planner. The result is a multi-sectoral Ramsey model with jelly capital, in which firms are essentially static entities and capital accumulation is driven by the trajectory of consumption/savings decisions made by a representative agent. With forward-looking behavior, imposition of pollution control costs in a future period will then induce anticipatory changes in investment in advance of the regulations' entry into force. The extent of such changes, and how different the resulting time-path of the general equilibrium price vector might be relative to that simulated by a recursive dynamic model, depends on the magnitude of abatement costs, the degree of convexity in the cost of adjusting capital stocks, and the intertemporal rates of time preference and substitution.

One final point bears mentioning. Multi-sectoral primal-dual perfect-foresight models with multiple capital stocks (either capital that is sector-specific or aggregate stocks that distinguish different kinds of assets, such as equipment and structures) tend to be difficult to calibrate (especially when the stocks represent different capital assets with divergent rates of depreciation) and computationally intractable. For this reason they are seldom used.

Although this discussion has focused on CGE models, none of the issues raised therein are unique to economy-wide general equilibrium approaches. Precisely the same points can be made regarding single-industry, multi-sectoral or other partial equilibrium simulations. The main distinction is that the latter are not particularly capable of capturing welfare impacts.

(iii) The number and type of sectors impacted

This is the key determinant of the appropriateness of economy-wide, in particular multi-sectoral CGE, models for regulatory impact analysis, for as noted in response C1 it is the regulated sector's forward and backward linkages that determined the impact of the regulation on output prices in the market for its products and factor prices in the market for sectoral inputs. In turn, these price changes are responsible for the ultimate impact of the regulation on households' consumption and welfare, the former is responsible for substitution effects, while the latter generates income effects, and together they determine the aggregate consumption vector and the value of the economy's utility index. There is no hard and fast rule for the number or type of sectors affected that justify a CGE approach; rather, the considerations should be those in response C1: whether there are strong cross-price effects between markets, and whether pre-existing distortions are present in those markets.

(iv) The details needed to represent the shock

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, the social accounting matrices (SAMs) used to parameterize CGE models have a high level of sectoral aggregation, leaving discrete industries or processes which may be the target of air pollution regulations bound up with other, potentially unregulated, activities. Notwithstanding this, if the goal is to analyze a regulation that targets multiple processes (perhaps across a range of sectors used intensively by households and/or downstream industries, it is nonetheless possible to disaggregate the processes in question as sub-sectoral technology-specific production or cost functions within the CGE framework. 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, calibrate the resulting benchmark model with discrete technology detail, and then debug the newly parameteized 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 which may be of more interest to EPA.

It is not clear what precisely the question means by "transition costs". This term could equally be applied to (static) intersectoral immobility of factors, such as capital or labor market rigidities which impedes the reallocation of factors necessary to allow their marginal products to re-equilibrate in the presence of the regulation. Or it could apply to (dynamic) capital adjustment costs that attend additional investment in pollution control mandated by regulation, or it could apply to costs associated with regulated producers' substitution among discrete technology options that are not adequately captured by smooth sectoral production or cost functions of the type typically used in CGE models. This response focuses on the last alternative.

Considering discrete production processes, one way of thinking about transition costs is in terms of stranded assets within regulated industries. Modeling this requires a 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 endogenously "switch on" and produce a quantity of output that is determined by the interaction of the regulatory stimulus and input prices. A second necessary element is 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. A potential third element is 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. Perhaps the simplest is not to focus on capital per se, but simply to model the pollution control/alternative technology as having a markup over and above the conventional technology's operating cost. In this way, mandating a shift toward the alternative technology increases the cost of production of the sector in question, with the expected knock-on general equilibrium effects. For this reason, the cost markups of alternative discrete technologies are a key engineering uncertainty that drives variation in the price, substitution and welfare impacts of a regulation.

(v) The appropriate degree of foresight

This is very much a question of "horses for courses". In intertemporal CGE modeling there is a clear computational tradeoff between static size/extent of technological detail, and the length and granularity of the time horizon that a model is capable of simulating. Thus, if the focus of the analysis is on specific sectoral or technology detail, then static, one-shot or recursive dynamic CGE modeling approaches may suffice. However, if the focus is on anticipatory investment dynamics in the run up to a regulation whose time-horizon for implementation is relatively short, then an intertemporal CGE model would likely be more suitable.

One way of addressing this dichotomy is via a top-down/bottom-up modeling framework which utilizes an intertemporal CGE model in conjunction with a partial equilibrium techno-economic model that embodies the desired engineering detail in target sectors. The CGE model simulates trajectories of prices and investment which are used as inputs to the engineering model, while the latter computes technology capacities and output supplies that are used by the CGE model as quasi-endowments. The two models are run in an alternating fashion, iterating until both their solutions converge. This approach, while attractive, requires substantial time and effort to calibrate the linked top-down/bottom-up modeling system. Linking models is discussed further in response C6.

(vi) The closure assumptions about international trade

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

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

The degree to which these adjustments at the boundary of the domestic economy end up altering the general equilibrium price vector relative to that of a closed economy depends on the fractions of the regulated industry's gross output accounted for by imports and exports, the sector's share of the economy's total value of trade, the price elasticities of demand and supply for the relevant import and export goods, respectively, as well as the economy's openness to flows of financial and physical capital. Perhaps the simplest closure assumes a small open economy facing a fixed world price and infinitely elastic supply of imports that are perfect substitutes for domestic production, which constrains the admissible increase in the unit cost of the regulated sector. However, such a Heckscher-Ohlin-Samuelson trade scheme may lead to unpleasant and unrealistic "bang-bang" behavior in which the regulated sector's output declines to zero and is entirely supplanted by imports. For this reason CGE models commonly employ the Armington (1969) trade formulation which treats goods within the same sector produced for the domestic market, export and import as distinct differentiated goods that are imperfect substitutes. Questions of closure then focus on what is to be assumed about the economy's current account balance, in particular, whether there is some balance of payments constraint versus a deficit that can be financed by flows of foreign capital.

Stepping back from the details, two points are important. First, implementing an Armington closure in a standard primal partial equilibrium model would appear to be difficult if not impossible, as proper characterization of import substitution requires the feedback effects of endogenously changing prices. Thus one would at least need a Takayama-Judge style primal-dual spatial price equilibrium model. Secondly, depending on the size of the regulated sector, trade may not be important for economy-wide costs, but it will certainly be critical to assessing the likely economic consequences for the sector's output, market share and profitability (as indicated by the change in the return to its capital). This is potentially interesting not only for analyzing the distribution of the economy-wide burden. In the climate change mitigation literature, a voluminous body of work has arisen that attempts to quantify the optimal tariffs necessary to offset international leakage of GHG emissions (and shore up output and capital returns in abating sectors) when a subset of countries pursues unilateral climate mitigation policies and GHGs are embodied in internationally traded commodities. Studies have found that the welfare costs of such border carbon adjustments can be substantial, especially relative to alternative policies. To the extent that the regulations envisaged in the charge might involve technology mandates packaged with offsetting quid pro quo protectionist measures such as border adjustments, it will be important to evaluate the welfare impacts of each component as well as the total package. That is something that only a CGE model can do.

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

Taking this point further, the vast double dividend literature points to the importance for economy-wide costs of interaction between the additional regulatory distortion and pre-existing distorting tax instruments (as noted in response C1), especially on factors whose endowments exhibit some degree of price elasticity (e.g., payroll taxes when households can use their time for work or leisure). But this highlights yet another aspect of closure, namely assumptions regarding the government's budgetary balance and fiscal components of regulations that are price-based and generate substantial tax revenue. These assumptions have been shown to be quite important in the case of, say, economy-wide taxation of GHG emissions. For more narrowly targeted regulations that primarily involve pollution control mandates, their criticality is less clear.

In summary, no PE model can even come close to capturing the breadth of the aforementioned effects and interactions, and this highlights the merit of using a CGE model.

(vii) The costs associated with model development

From a cost perspective, the largest expenditure in constructing, calibrating and debugging an economic model is labor: both to code the simulation program and to assemble the underlying data used for parameterizing the model. It is comparatively rare to find economics and public policy PhDs who are trained in CGE modeling, and as such there tends to be excess demand for the particular set of skills necessary to construct and simulate economy-wide GE models, especially when a requirement of such models is that they incorporate substantial discrete technology detail. Engineering or operations research graduate programs produce PhDs trained in optimization modeling in larger numbers, and a larger supply of individuals with the skills necessary to construct and simulate partial equilibrium techno-economic models would seem to suggest that an equivalent demand for PE models might be satisfied more readily, and perhaps at lower cost, though this may be blunted by model building is a highly differentiated service, which allows modelers to engage in monopolistic competition. The latter point also suggests that there are differentiated markets for PE and GE modelers, which does play out in practice. The effort and psychic cost necessary to grasp and effectively implement the logic of GE tends to be a substantial barrier to employing individuals trained as PE modelers to build CGE models, but the reverse tends not to be true. GE modelers can and (because of their economics training, and the demand for CGE models with technology detail that necessitate the implementation of linear and nonlinear programming routines for calibrating bottom-up parameterization strategies) often do work on PE models as well.

On the benefit side of the ledger, the singular advantage of GE modeling relative to other analytical approaches lies in the economic logic of the general equilibrium framework, in particular its ability to enforce a consistent accounting of the factors responsible for determining the economy-wide costs of a regulation, and thereby discipline the entire regulatory impact analysis exercise. Properly conducted, CGE modeling is thereby capable of providing the most transparent and rigorous way to track the economy-wide costs of regulation, and is the only way to consistently estimate aggregate welfare impacts.

(viii) The ability to incorporate uncertainty

This is not a strength or weakness of economy-wide models per se. The most important driver of the underlying uncertainty is the provenance of the engineering data on which bottom-up technology-level costs, and their attendant uncertainties, are to be calculated. From that point, there is a question of how much of a difference alternative estimates of engineering performance parameters makes to the parameterization of a CGE model that seeks to incorporate technological detail. The modeling literature has paid comparatively little attention to the extent to which either (i) differences in engineering characteristics translate into differences in the input cost shares of the technologies in question within a social accounting matrix framework, or (ii) how the latter variation in cost shares might affect the price and substitution adjustments, and ultimate welfare impact, computed by a model with a given sectoral structure on which particular regulatory constraints are imposed. That this issue is not unique to CGE models becomes clear once one realizes that all partial equilibrium techno-economic models do is simply collapse uncertainties (i) and (ii), yielding information on how the sensitivity of the optimal solution varies to the characteristics of the technology set. However, what the discussion here implies is that, should there be a wide range of outcomes in (i), additional sensitivity analysis and testing would be required to characterize (ii), with the potential for attendant increases in modeling effort and cost relative to partial equilibrium approaches.

Cost Question 3 (C3)
Lead: Balistreri

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?

Model validation and reliability for policy decisions are additional important considerations. This is an area of limited research, but an important consideration. While other methods of analysis (econometric models) have built-in, well established, indicators of validity, many CGE models are constructed using data sets having limited time spans and are thus saturated in terms of the number of parameters relative to the information provided by the data. This makes validation tricky. Both parametric and structural sensitivity are important considerations. The goal remains the provision of 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.

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

Below we list a number of other factors that are relevant to the assessment of the social costs of regulation.

1. Intertemporal models that do not include forward-looking perfect foresight decisions can be problematic because they include an implicit distortion related to savings behavior. This distortion can interact with the policy shock in unpredictable ways. In contrast, it can be difficult to defend perfect-foresight models in a policy context because it requires that economic actors have perfect expectations and knowledge of all policies in all

periods of time covered by a modeling exercise. The dynamic structure of a particular model application should consider these trade-offs.

2. Market structure is often very important in gauging regulatory effects, while the tradition in CGE analysis is to assume perfect competition.
3. As noted in response C1, existing distortions (i.e., existing taxes, subsidies, imperfect competition, and fiscal reactions to policy) are critically important to represent explicitly for cost analyses and should be captured in models wherever possible.
4. There may be important endogenous impacts of policy on productivity growth and technological change.
5. There may be important interregional or international flows of capital and labor related to policy interventions. The general assumption that labor is immobile across regions can be problematic, especially when modeling subnational regions.
6. The quality of subnational social accounts is suspect because they are often based on apportioning national benchmark accounts in a way that would obliterate the targeted heterogeneity.
7. The public finance implications of regulation and its interaction with investment.

This list is not intended to be completely exhaustive, but rather highlights certain considerations in modeling relevant policy questions. It is important to maintain and foster a close connection with others engaged with similar research questions. To this end the principles of data and model availability for peer review are critical for credible analysis. Continued participation of EPA analysts in professional meetings and peer-reviewed publications will be important in keeping EPA analysts in touch with the modeling community. Many of the important considerations for assessing whether and how to model the social costs of regulation in an economy-wide framework are only revealed through interactions with other experts through the professional forums.

Cost Question 4 (C4)
Lead: Fisher-Vanden

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 air basin 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. Economy-wide models are usually too spatially and sectorally aggregate to capture air basin-specific regulations. It is also difficult to predict what each air basin will do to comply with the NAAQS.

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

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

Economy-wide models should account for any such constraint that would have a significant effect on output.

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 but they should, nonetheless, be recognized.

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

It is possible that non-price regulations could be modelled as their price-equivalents, using tax and subsidy combinations. (A forthcoming paper in AEJ-Policy by Goulder, Haefsted, and Williams may be instructive in this regard). However, there are potential challenges associated with implementing this approach; for instance, how to identify what should be taxed when it is not always clear which sectors will be affected and by how much; how to implement the tax when there may be changes to the input process in response to the regulation; how to treat the timing of shifts in input responses. In order to implement the non-price regulation as a price-equivalent regulation, detailed price representation in the model is required, as detailed as the regulation itself. This raises the question of how many price margins can be incorporated into a model, and what matters most with respect to their representation.

For some regulations, EPA may have already identified the specific technology it expects industry to use to comply with the regulation and its associated costs; however, it is not clear how to credibly introduce this information into an economy-wide model that doesn’t have the same industry structure or representation as used in the engineering analysis. For example, in the case of CAFE standards, engineering analysis never contemplated the cross-elasticity of substitution between light trucks and passenger cars. CGE models would be more advantageous in picking up these elasticities if only because they remind the analyst that such elasticities are needed.

Cost Question 5 (C5)
Lead: Metcalf

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

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

Utility functions are 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 money amount is a cash equivalent to the total impact of the regulation (including changes in consumer prices, changes in wages or returns to capital, or restrictions on behavior).[1] This measure has a long history of use in economics dating back to Hicks (1939) and is an essential tool taught in both undergraduate and graduate level microeconomics. See, for example, Mas-Colell, Whinston & Green (1995).

While the question refers to the use of EV in CGE models, it is important to recognize that EV can be used in PE models as well. All that is required is a representation of each consumer's utility function (defined over goods and services) and the consumer's budget constraint or, equivalently each consumer's indirect utility function (defined over prices and income and

[1] 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.

subsuming optimizing behavior on the part of the consumer).[2] Its use in a PE framework is only sensible if the regulation in question affects only one market without spillovers across markets. Of course, this is precisely the condition required for a PE analysis to be meaningful.

Besides being theoretically motivated and straightforward to measure, individual EV's can be summed to provide an aggregate measure of the social cost of a regulatory policy.[3] Besides being motivated by a sensible theoretical framework ("how much would I pay to avoid this policy?"), an EV measure requires an underlying utility function. The appeal is that it makes transparent the goods and non-market services included in the utility function.

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

The EV measure has two major drawbacks. First, it cannot be used in bottom up engineering models of regulatory costs. We view this less as a drawback of EV than a drawback of engineering models. What this observation tells us is that engineering models can measure a subset of regulatory costs – the direct compliance costs to the firm. What such models cannot measure is consumer responsiveness to those higher production costs including any possible averting behavior by consumers to avoid higher consumer prices (e.g. substitution in consumption).

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

[2] 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 thought experiment, though it does approximate EV or CV when income effects from the price change are small.

[3] 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 cost benefit 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.

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

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

To see a second major flaw with using GDP or consumption as a welfare measure, consider a policy to extract more natural resources today, sell those resources, and use them to produce more goods for consumption. The resulting increase in GDP or consumption would overstate the increase in welfare, because it does not account for the depletion of those natural assets. Similarly, we can view clean air as a natural asset. Any change that uses up some of that clean air (by creating additional air pollution) could increase both GDP and the normal measures of consumption of goods and services, but it would not account for the loss of that natural asset. Conversely, a policy to clean up the air might reduce normal measures of GDP or consumption even though those measures miss the increased valuation 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 are using 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 As a result scrubber investment, is a cost arising from the regulation not a benefit or cost reduction., which, appears to raise welfare in an absolute sense even though its true net impact is zero.

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.

Cost Question 6 (C6)
Lead: Fox

Charge Question C6: What conceptual and technical merits and challenges are important to consider when incorporating and potentially linking of detailed sector cost models or bottom-up engineering estimates of abatement costs with a CGE model?

Since federal air regulations are inherently sector- and region-specific in their costs and benefits, some type of linking of bottom-up and top-down models will often be necessary to deliver national scale assessments of such regulations. As noted in US EPA (2015a), there are many different ways to link models for the assessment of air quality regulations. So it is useful to begin by reviewing 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.

A. Soft linking: This refers to extracting information from sectoral models and inserting it into a CGE model (with the possibility of feedback loops). This is the simplest form of model linking and therefore commonly used for preliminary estimates. It is only really appropriate for one-off ball-park analysis, since it does not provide any type of analytical or data consistency between the two models and therefore can easily be misleading. Soft linking is therefore inadequate for serious regulatory analysis.

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

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

C. Sequential calibration: This is a more sophisticated means of linking two models, invented by Tom Rutherford, and applied to many different problems. It was originally intended to facilitate linking of a bottom-up electricity model with a top-down CGE model. Its implementation is relatively straightforward. A constant elasticity supply function (e.g., for electricity) is introduced into the CGE model. The two models are then run in sequence, successively recalibrating the supply function until the equilibrium price and quantity of electricity is in agreement between the two models. Experience suggests that this tends to converge rather quickly, thereby ensuring that, for the common variables, the two models are in agreement. However, if the power-sector regulation encourages capital-intensive renewable energy technologies, for example, this increased demand for capital should be carried over in the integration with the CGE model. Otherwise, sequential calibration would fall short of providing the full set of general equilibrium impacts of the regulation.

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

How does one determine the extent of inter-sectoral linkages and the need for CGE analysis?

It would be very useful for EPA to have objective criteria for making such a determination as to when a policy or sector might be sufficiently linked to the rest of the economy to justify CGE analysis. A consistency or comparative-accuracy criterion, based on the use of an existing CGE model to investigate the sector-level, equilibrium elasticities of demand, represents one such approach. Specifically, by computing the partial and general equilibrium elasticities of demand, and comparing them to a pre-determined threshold deviation, an objective determination could be made to decide when these general equilibrium linkages are sufficiently important to justify employing CGE analysis (Hertel et al., 1997).

For example, the equilibrium elasticity could be obtained by incrementally perturbing an output tax in the regulated sector such that the market price for output rises by 1%. The resulting contraction in output can be interpreted as the equilibrium elasticity of demand (since price rose by exactly one percent). Whether this is a partial or a general equilibrium elasticity is determined by what adjustments occur in the rest of the economy. A partial equilibrium closure would typically hold consumer incomes constant as well as quantities and prices in other sectors. In the factor markets, wages might be fixed exogenously while capital could be sector-specific (short run) or perfectly mobile (medium run). In contrast, the general equilibrium demand elasticity would account for endowment and budget constraints, allowing all prices and quantities in the economy to adjust. By considering the difference between these two elasticities, one could evaluate the importance of cross-sector, economy-wide effects of regulating the sector of interest. This difference could be compared to a pre-determined threshold, e.g., a 10% deviation. If this threshold were exceeded, then this could be grounds for moving to a CGE framework.

Consideration could also be given to the potential impact of sectoral regulation on inputs to other economic sectors, e.g., energy. If a proposed regulation would induce a sufficiently large change in the price of electricity or petroleum—5% per year for example—then there might be enough influence on fuel substitution in other sectors and across the general economy to warrant GCE analysis of the proposed regulation. If detailed models of a sector are available, either engineering-economic or partial equilibrium, then incorporating them or their outputs into a CGE framework may be warranted.

Cost Question 7 (C7)
Lead: Shimer

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?

In addition to striving for a modeling approach that yields accurate estimates of the economy-wide effects of proposed regulations, EPA should choose an approach that is transparent and reproducible. Transparency and reproducibility are important because minor changes in scientific or economic assumptions could lead to dramatic changes in forecasted costs (or benefits) from a regulation. If the sensitivity of a model is obscured, it might be perceived as turning with political tides, which could be harmful to the integrity of EPA. Second, changing regulations create an uncertain environment for business investment, which can reduce the average level of investment and output (see Bloom, Econometrica, 2009).

The appeal of a CGE model lies, in part, in its comprehensiveness and hence potential accuracy. A single model can potentially describe all of the costs (and benefits) of proposed regulations. Unfortunately, this is also the weakness of CGE models. Some part of a CGE model will inevitably be mis-specified. Depending on the model, a small misspecification in one part of the model can lead to dramatically incorrect conclusions elsewhere. Moreover, by their very nature, CGE models are complex and may thus be difficult to discern the quantitative importance of different links between parts of the model. If CGE models are not transparent, their results are not easily reproducible and are therefore less credible.

An alternative to CGE modeling is to take a more eclectic approach combining standard simulations of engineering and PE models to provide a useful starting point for the analysis of any regulation. These models are relatively transparent and EPA has tremendous expertise in working with them. Unless scientific knowledge and its implementation changes, the estimated costs from an engineering approach will not change quickly over time.

CGE, other general equilibrium models, and existing empirical and theoretical research, may then suggest aspects of the PE approach that are misleading. The goal of an eclectic approach is then to extend the PE model to incorporate the most important such dimensions. There are several advantages to this approach over CGE modeling alone. It is possible to devote more resources to analyzing the particular issues that are likely to be most relevant to the proposed regulation, thereby drawing on the most current available research and obtaining more accurate answers. The impact of economy-wide modeling can be made transparent by separately enumerating the additional costs (and benefits) introduced by each of the extensions. And for many proposed regulations, it will make sense to extend the partial equilibrium model along similar dimensions, thereby allowing EPA to develop expertise on these issues.

An example might be useful. Suppose EPA believes that a proposed regulation is likely to contract some parts of an industry, thus leading to layoffs. A large empirical literature addresses the impact of layoffs on prime-aged workers. For example, Davis and von Wachter (2011) find that when such a worker loses his job, he suffers a protracted decline in labor earnings. In present value terms, a worker loses 1.4 years of earnings when he is laid off during a period with low unemployment and twice as much when he is laid off during a period when the unemployment rate is above 8%. Although this research does not exclusively look at layoffs due to regulatory changes, there is no particular reason to think that foregone earnings are likely to be significantly higher or lower in such cases. Therefore earnings cost estimates of layoffs (partially offset by changes in workers' available leisure time) should be added to the costs from a partial equilibrium model.

In contrast, to capture these costs in a CGE model would require a dynamic model that generates large and persistent earnings losses following a layoff. To our knowledge, such an economy-wide model does not exist because it would require a very fine-grained submodel of the labor market, distinguishing between workers by occupation, industry and region, as well as requiring parameter estimates for the rate at which laid off workers move between jobs. Moreover, unless a CGE modeler explicitly seeks to analyze the earnings loss following displacement, she would be unlikely to realize that the model significantly under-predicted the costs of displacement, particularly since CGE models are so complex. For this reason, existing CGE models likely understate the costs associated with regulations that displace workers from their jobs. Employment aspects of economy-wide modeling are discussed in more detail in responses D3, D4 and D5.

In some cases, the eclectic approach will point out certain key areas where there is little evidence or consensus on how the economy will respond to a proposed regulation. Highlighting such underexplored areas can be useful for spurring additional research both within EPA and within the broader research community. In contrast, the CGE approach is less amenable to generating clear statements about areas where future research is particularly valuable.

In response to a mandate in the 2016 budget resolution that required a move from static to dynamic scoring, the Congressional Budget Office (CBO) and Joint Committee on Taxation (JCT) have taken an approach similar to the one described here. The CBO used a behavioral Solow growth model and an optimizing overlapping generations model to find two 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. It may be useful for EPA analysts to talk with economists at the CBO and JCT to get a better idea of the challenges and advantages offered by this alternative. Edelberg (2015) is a presentation describing CBO's current approach to dynamic scoring.

Benefits Question 1 (B1)
Lead: Muller

Conceptual and technical hurdles to representing benefits

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

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

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

The question of *how* a CGE model is aggregated may determine whether there are adverse consequences of representing spatially heterogeneous air pollution benefits in a national CGE model. For example, aggregating according to airsheds rather than administrative boundaries would help align the model with exposure to pollutants, although it would still not capture intra-airshed variability. However, realigning a CGE model according to airsheds may not be necessary if economic 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 general equilibrium benefits of air regulations are expected, the next question is whether the feedbacks themselves will vary spatially. If such general equilibrium effects are not expected to vary across space, then the aggregated approach may be adequate. If the feedbacks are liable to exhibit heterogeneity, then the modeler faces a decision as to whether geographically disaggregated approaches are justified for all sectors, or if disaggregation could be targeted at particularly relevant sectors.

In view of the current empirical evidence that suggests that benefits of air pollution regulations are primarily due to reductions in premature mortality risks, it is important to consider how reduced mortality benefits will have general equilibrium effects. As such, a channel through which such benefits may have general equilibrium effects is through the time endowment. However, if this is the primary linkage between air pollution policy and benefit feedbacks and the labor supply is relatively mobile, then the advantage to a spatially disaggregated CGE model is likely to be low.

Beyond characterizing the type of benefits (mostly premature mortality risk reductions), whether there are general equilibrium effects (if so, primarily through the time endowment) and whether or not these vary across space (not if labor supply is mobile), an important issue is that the magnitude of these effects are such that there likely are important general equilibrium impacts. In particular, the benefits of the Clean Air Act have been estimated to be between 15% and 20% of wage income. 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?

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 is 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 accuracy and this component adds to the difficulties associated with using spatially-disaggregated CGE models.

Additional obstacles or challenges associated with representing benefits of air regulations in a general equilibrium framework include: modeling regulated firms' actual responses in the face of myriad policy constraints (see response C4), the disparity in valuation techniques applied in non- and CGE contexts (see response B2), 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.

Many prior analyses that estimate the monetary benefits of air pollution policy employ valuation techniques based on WTP measures, such as the Value of a Statistical Life (VSL).[4] 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 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. While reconciling these differences is not the responsibility of CGE modelers, recognizing that the benefits of air regulations (and environmental policy, more generally) extend beyond the market boundary is important.

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

[4] See EPA (2010f) for a detailed discussion of the process of valuing reductions in mortality risk that underlie VSL estimates, as well as a review of the empirical literature.

Benefits Question 2 (B2)
Lead: Carbone

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

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

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

Both methods aim to capture the effect of changes in mortality generated by the policy. Beyond this similarity, however, the two measures may diverge for a number of reasons. In the discussion that follows, we primarily focus on mortality risk reductions because it is the single-most important category of benefits in benefit-cost analyses of major air quality regulations.

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

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

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

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

The expression contains a couple of important insights. First, it makes clear that VSL should capture the value of non-market assets and consumption.[5] For example, extending the lives of retirees generates no additional earnings but clearly has economic value. CGE applications that fail to account for non-market activities (including the value of leisure time) are likely to underestimate the value of life extension for this reason.

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

Beyond this broad correspondence, however, differences in the treatment of any of the terms in the VSL expression represent opportunities for CGE and VSL-based calculations to diverge. In particular, the surplus generated by consumption in CGE models will depend on the parameterization of the agent's utility function. Unless the utility function is estimated with empirical estimates of VSL or a source of data capable of identifying risk reductions, , we have no reason to expect CGE and VSL-based measures of mortality impacts to have any relationship to each other.

Perhaps an even more basic reason these measures may differ is because the standard VSL-based calculations are not embedded in a complete demand system. Conceptually, VSL captures

[5] Murphy and Topel 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.

willingness to pay for a small change in risk. Using it to evaluate the benefits of large risk reductions could overstate the benefits by failing to acknowledge the limits imposed by budget constraints and the effects of diminishing marginal utility – both features that are present when modelers use a utility-maximization approach to measure welfare impacts.

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 breed of CGE models that can incorporate VSL information would be required to produce comparable benefits estimates from using the two methods.

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

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

Moreover, many of the techniques used by economists to value environmental quality are predicated on the belief that the environment is either a complement or substitute for some market-based activity. Observing how the demands for these related goods vary with environmental quality allows us to infer its value. At the very least, this points to a logical inconsistency between the models used to estimate the value of environmental quality and the way these estimates are employed in benefit-cost analyses. Whether it represents more than a logical inconsistency is an empirical matter that remains to be explored, but 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 response to question C1).

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

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

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

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

The same logic applies to the task of including non-market values from improvements in environmental quality into a CGE model. Households are endowed with a level of services derived from environmental quality in the benchmark equilibrium to which the model economy is calibrated. The shadow price used to place a value on this endowment is an empirical estimate of the aggregate marginal willingness to pay for improvements in environmental quality. The agent then assesses her full income, including conventional market-based components as well as the value of the environmental endowment, in choosing consumption activities. How environmental services enter the agent's utility function controls the degree to which the environment functions as a substitute or complement for the other consumption activities described in the model. In policy experiments, the environmental impacts of new regulations are reflected in changes in the size of these endowments.[6]

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 precisely definitive estimates of policy benefits. For example, interactions between environmental quality and other elements of the demand system are matters on which we have scant empirical evidence. Sensitivity analysis is essential.

Perhaps the most important point to be made here is that expecting CGE models to provide more precise estimates of benefits than other approaches is to misunderstand what this set of tools has to offer. The method's strength lies in its ability to function as a laboratory in which researchers can test which interactions matter and which are unimportant. If general equilibrium interactions are shown to matter little for determining benefits of a particular air quality regulation, non-CGE approaches are sufficient. If some interactions do appear important, a CGE approach is warranted. To determine which such interactions are important, an approach analogous to that discussed in response C7—for determining when general equilibrium effects are most important for assessing costs—could be used.

[6] 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 static CGE models, where explicitly modeling a stream of future benefits from life extension is not possible. Dynamic models could, in principle, follow a strategy derived from the logic of Murphy and Topel (2006). These are issues that remain to be explored.

Benefits Question 3 (B3)

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?

Benefits Question 4 (B4)
Lead: Paltsev

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

Modeling a change in the time endowment is technically feasible, but other channels for the impacts of reduced $PM_{2.5}$ exposure (like labor force participation, change in health care services and expenditures) should be considered as well. Mortality and morbidity impacts can be modelled as changes in market effects (lost wages and expenditures on health care) plus some valuation of the non-market effects of illness—pain and suffering and associated loss of enjoyment or attention to household activities because of the illness. In a CGE framework, the components of these valuation estimates can be included. Specifically, hospital costs can be treated as a demand for medical services, lost work time can be treated as a reduction in the labor force (in dollar equivalents), and damages beyond these market effects can be treated as a loss of leisure. Yang et al. (2004) use this approach and provide a methodology for integrating health effects from exposure to air pollution into a CGE model. Matus et al. (2008) apply this method to examine the economic consequences of air pollution on human health for the U.S. for the period from 1970 to 2000. The Matus et al., (2008) study addressed benefits from reductions in tropospheric ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, and particulate matter. Other examples of the studies incorporating cost of illness, lost work time and loss of leisure are Nam et al. (2010), where welfare losses caused by air pollution in Europe are estimated, and Matus et al. (2012), where health damages from air pollution in China are assessed.

To incorporate mortality and morbidity impacts into a CGE model, detailed emissions-impact relationships, including information from source - receptor atmospheric modeling and updated information on concentration-response functions and associated costs are needed. Examples of studies that provide information on concentration-response functions are Holland, Berry, and Forster (1998) and Pope, et al. (2002). Based on the detailed emissions-impacts relationships, Burtraw, et al. (2003) provide an examination of health effects from changes in NOx emissions in the electricity sector and calculate ancillary benefits from modest carbon taxes. An air quality modeling system is linked to a U.S. computable general equilibrium economic model in a study by Saari et al. (2015) where they also use emission-impact relationships to represent the economy-wide welfare impacts of fine particulate matter. Another approach for incorporating the economic impacts of air pollution includes estimates of willingness to pay (WTP) for reduced health risks (Bell, Morgenstern and Harrington, 2011). WTP estimates for reduced mortality risk are discussed in responses B2 and B5.

Benefits Question 5 (B5)
Lead: Smith with Montgomery additions

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?

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

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

- Do they offer sufficient resolution for specific pollutants that would match the detail of the damage function research? –NO
- Do they offer sufficient coverage of different urban areas to be used on a national scale in lieu of that damage function approach? – NO

- Can these health effects be isolated from other motivations for avoiding air pollution? – NO
- Have these studies been tested for spatial confounding effects of unobservables? There is at least one study with these types of tests in the hedonic context. It relates to early experience (Chay and Greenstone, 2005). Based on Kuminoff and Pope (2014) evaluating hedonic models in a different application one would raise issues about how these types of estimates should be interpreted.

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

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

The use of preference calibration strategies would yield a wider range of estimates for VSL. More generally, this logic (see Smith et al., 2002) addresses issues that are similar to what must be considered in introducing non-market services into CGE models. As noted in response B2, these issues arise from considering how the tradeoff measures recovered in different contexts—labor markets with hedonic wage models, labor markets with labor supply models, or hedonic property value models--relate to a single economic model of individual preferences.

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

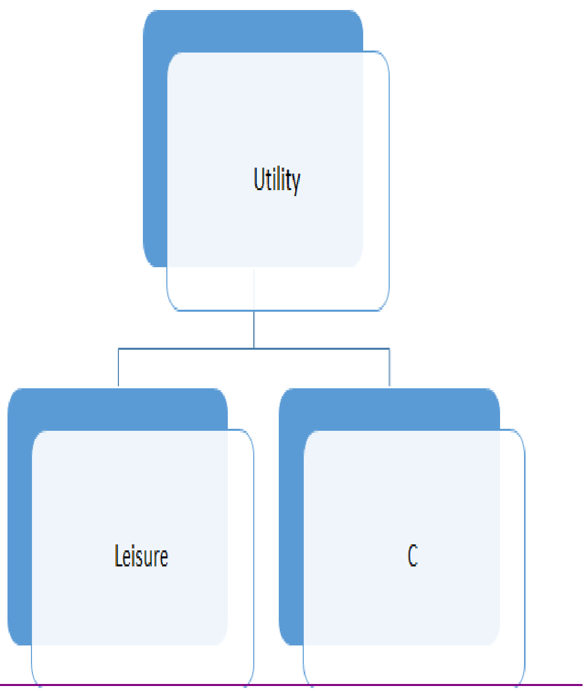
Given adequate data or appropriate parameters from the literature, it is a straightforward programming exercise to extend a CGE model to include these features. Examples of models that deal generally with the representation of material flows and externalities do exist in the literature [Ayres and Kneese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

The tree diagrams below represent how morbidity and mortality can be incorporated in a CGE model on the production side and the consumption side. These are drawn for a single representative agent that has preferences over both marketed and non-marketed goods and services. Each industry is characterized by a production function that uses capital, labor, non-marketed goods and goods produced by other industries. These are combined to produce one type of good plus pollution (positive outputs indicate additions to the availability of goods that the representative agent would pay a positive amount to increase and negative outputs indicate subtractions). The pollution could be considered a joint output creating demand for the receptacle services of one or more dimension of the natural environment.

Figure 1 is the simplest CGE model with no non-market goods or health effects. The representative agent gains utility from both leisure and consumption, and has an endowment of time that can be allocated to labor or leisure, as well as an endowment of the existing stock of productive capital. The parameters of this utility function determine the labor supply elasticity. Income is obtained from labor and capital and is used to purchase consumption goods subject to the budget constraint. The production function represents feasible combinations of pollution and consumption goods that can be produced with a given amount of labor and capital.

In Figure 2 we introduce the relationship between pollution and health effects. To model health effects, the time endowment is reduced by sick days and early mortality. Morbidity and mortality are connected to pollution by a health outcomes function, which sums up the results of both air quality and health effects modeling into a function with dimensionality appropriate to the speciation of pollutants and regional and demographic disaggregation of the CGE model.

The VSL is another way of expressing the value of the marginal willingness to accept a small increase in the risk of death. When expressed as a VSL, it aggregates these values across the number of individuals who would need to experience the risk change for the expected number of deaths to be one. In this formulation, one considers death as causing a loss of labor time then the VSL is measuring the amount of income required to compensate for the value of lost consumption caused by 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 response B2 as well).



Constraints

Income = Wage*Labor + Rate of Return*Capital

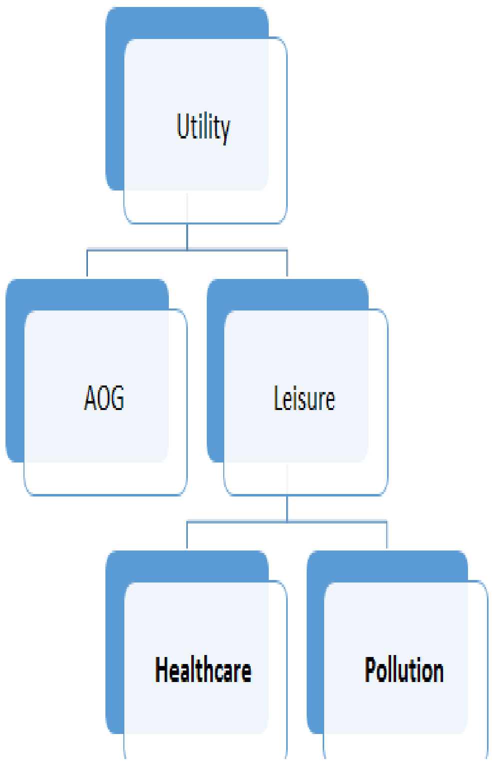
Budget: Income – Pc*C = 0

Time: Labor + Leisure = time endowment – sick days – early mortality

Production: F(C; Labor, Capital; Pollution) = 0

Health outcomes: G(sick days, mortality, pollution) = 0

Figure 1: Utility as a Function of Leisure and Consumption



Constraints

Income = Wage*Labor + Rate of Return* Capital

Budget: Income – Ph*Healthcare – Pa*AOG = 0

Time: Labor + Leisure = time endowment – sick days – early mortality

Production: F(AOG, Healthcare; Labor, Capital; Pollution) = 0

Health Outcomes: G(sick days, mortality, pollution, healthcare) = 0

Figure 2: Two-Tier Utility Function Including Healthcare and Pollution

Figure 2 introduces the healthcare system in the most general way. In this case capital and labor are inputs to production of healthcare, all other goods (AOG) and pollution. Income can now be spent on consumption or on healthcare. Healthcare does not itself enter into the utility function; increased mortality and sick days reduce income.

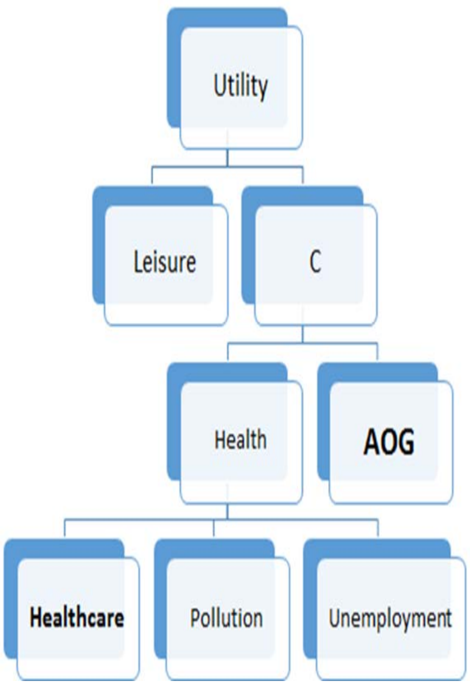
Healthcare can also affect health outcomes, and in general the effects of increased pollution on sick days and mortality can be reduced by additional healthcare expenditures. Thus this formulation properly categorizes healthcare as an intermediate good that produces a valuable good—more time for labor or leisure—and does not show up as providing welfare directly. Because of this, increased pollution will lower welfare (through redirection of expenditure from utility-producing goods to health care, as well as from increased sick days and mortality that are not completely prevented by health care) more than it reduces GDP (which only falls by the wage value of the incompletely-prevented sick days and mortality).

In a more elaborate formulation shown in Figure 3, the representative agent could be represented as consuming (gaining positive welfare from) health and other goods. In this case, pollution and healthcare would be represented as inputs to a health outcome function that also determines sick days and mortality. Good "health" is not itself a marketed good, but a result of healthcare and environmental factors. Thus in this formulation healthcare is (as above) an intermediate good, much like gasoline can be an immediate 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 response B2, putting health into a utility function used in a CGE model does imply 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 and are needed to ensure existence of an economic equilibrium:

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

There is also the interesting implication that except in special cases, decreasing pollution will decrease healthcare expenditures and produce lower values for the mitigating activities related to the health effects of pollution but greater welfare benefits than stand-alone health effects models predict (since they would hold healthcare expenditure constant). This is a very general economic principle but one that can only be captured with an appropriate utility specification.



Constraints

Income = Wage*Labor + Rate of Return * Capital

Budget: Income – Pa*AOG = Ph*Healthcare = 0

Time: Labor + Leisure = time endowment – sick days – early mortality

Production: F(AOG, Healthcare; Labor, Capital; Pollution) = 0

Health Outcome: H(health, sick days, mortality; healthcare; pollution)

Figure 3: Three-Tier Utility Function Including Health and Unemployment

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

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

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

A subset of the contingent valuation (CV) research has adopted the approach of describing the object of choice posed to respondents as "plans" to improve some aspect of environmental quality. See Richard Carson (2011) for a bibliography of CV studies.

Other support can be found in the quasi-experimental literature where regulation is treated as an external effect on behavior that is hypothesized to affect environmental quality. In these studies specific measures of the associated change in quality but may not be specifically introduced into the analyses.

There have been claims that regulations that have the macroeconomic effect of inducing unemployment or reducing incomes will also adversely affect health, and that this indirect effect should be included in cost-benefit analysis (citations to be added)[7]. However, as noted by Stevens et al. (2015), aggregate mortality is actually procyclical, with death rates rising when unemployment falls during economic expansions.[8] The authors attribute much of the procyclical mortality they observe to a general equilibrium effect: the increased difficulty nursing homes face when other employment prospects improve for relatively low-skilled workers. An additional, but considerably smaller component, is due to an increase in motor vehicle accidents during expansions.[9]

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

[8] The authors attribute much of the procyclical mortality they observe to a general equilibrium effect: the increased difficulty nursing homes face when other employment prospects improve for relatively low-skilled workers. An additional, but considerably smaller component, is due to an increase in motor vehicle accidents during expansions.

[9] The authors attribute much of the procyclical mortality they observe to a general equilibrium effect: the increased difficulty nursing homes face when other employment prospects improve for relatively low-skilled workers. An additional, but considerably smaller component, is due to an increase in motor vehicle accidents during expansions.

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

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

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

No such CGE models are currently available off the shelf for use in cost-benefit analysis. However, small aggregate models along the lines discussed with judgmental parameters for the connections between employment or income and health effects could be constructed with little difficulty, and would provide insight into the potential health consequences of regulations.

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?

The conceptual and technical challenges that were raised in addressing the first component of this question are relevant to this sub-question. That is, the answer lies in detailing the logic associated with providing consistent links between the tradeoff measures recovered for morbidity with the tradeoff measures for risk changes. The parameterization of CGE models forces these issues to be confronted.

The most direct approach for addressing whether the effects are too small to noticeably affect the quantitative results arises when the analysis evaluates the sensitivity of the parameters of a CGE model to the inclusion or exclusion of these measures from the process of calibration that has been used to recover these estimates. More specifically the linkages between what has been estimated and the model define a set of moment conditions. Calibration is the process of solving the nonlinear equations associated with these moments for the free parameters of the model.

Benefits Question 6 (B6)
Lead: Williams

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

In theory, the effect of employment on health and crime can be incorporated into a CGE model; however, doing so in a plausible and credible manner would go well beyond the frontiers of current knowledge and would require major investments in model development. Given these difficulties and EPA's limited resources, we do not advocate incorporating these effects at this time, either in a CGE model or any other economy-wide model. The fundamental issue is that the effects are the result of a complex multiple-link causal chain. Regulation affects employment; employment affects health and crime; and health and crime affect the costs or benefits of the regulation. None of the links in this chain is direct or simple to quantify.
For example, most CGE models explain the number of hours worked as the equilibrium of supply and demand in the labor market. These voluntary movements in hours are likely to have a very different impact on health and crime than changes coming from involuntary unemployment. Very few CGE models capture unemployment and long-term joblessness, so even this first link in the chain would put the model at the frontier of what is currently available. To our knowledge no CGE model considers the effect of employment changes on health or crime. Capturing this and then accurately valuing the resulting benefits would thus require a model that goes well beyond any that currently exist. For example, to capture the procyclical mortality discussed in response B5 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. To the extent it is feasible, we encourage EPA to 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 would be warranted.

Benefits Question 7 (B7)

Lead: Belzer

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?

Given the multifaceted nature of this question, we have answered it in multiple parts. First, however, we note serious complications that arise from the opaque pricing of medical care in the United States. Marginal price signals for medical care have been opaque for decades due to the predominance of third-party insurance typically but not exclusively provided as a nontaxable employee benefit. Since the establishment of Medicare and Medicaid in 1966, the elderly and poor also have been substantially shielded from marginal price signals, at least for covered conditions and indigent health care provided by right at no cost, such as through hospital emergency departments. Price signal opacity may have increased since the enactment of the Affordable Care Act (ACA) in 2010. The ACA added numerous coverage mandates such that prices to consumers for more medical care services are often trivial or free at the margin. The ACA also extended systemic subsidies to the non-poor (i.e., those with incomes less than 400% of the federal poverty line), thereby inducing even more allocative inefficiency. Mandated changes in the design of health insurance contracts have resulted in reduced competition, as insurers attempt to keep posted prices down through narrow provider networks. Price signal weakness in medical care is compounded by a common propensity to delegate much medical decision-making to professionals and the regulatory delegation of coverage questions to third-party insurers and health maintenance organizations.

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

This question is based on an assumption that some individuals experience beneficial changes in health status from reduced air pollution. While we believe this is a reasonable assumption, it is unclear to what extent we can relate improvements in health status to reduced medical expenditures given the opacity of the market for health care. Even where price signals are strongest—i.e., where there is no insurance and consumers are responsible for first-dollar payment—there may be substantial spatial differences in service quality within a community that consumers cannot discern easily, if at all. Similar difficulties afflict consumers when attempting to compare quality among providers even when prices are transparent. Dynamic improvements in service quality, some of which are dramatic, may make it impossible for consumers to disentangle price and quality. This is especially problematic for extraordinary medical interventions of the kind that reduced air pollution is said to prevent (e.g., cardiovascular events).

A serious confounder in both opaque and transparent medical care markets is dynamic quality improvement. These improvements span the gamut from pharmaceuticals to medical devices to patient care to best-practice guidelines. No published research appears to be available on the point, but it is far from clear that consumers would prefer 1995-vintage medical care at 1995 prices.

In short, medical care has become a non-market good in which reductions in consumer expenditures resulting from improved health status subsequent to reduced air pollution may be unobservable. This problem is magnified given coincident increases in the quality of medical care that also are extremely difficult to measure. For these reasons, and given the uncertainties involved, the income effect from reduced medical expenditures resulting from improved health status subsequent to reduced air pollution seems unlikely to be measurably positive.

The consumer could also experience changes in their [sic] 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?

As noted in response B5, demands for goods may not be separable from health status. Broadly considering the extent to which reduced air pollution could mediate changes in the marginal utility of consumption, especially for goods whose consumption is contingent on health status, EPA should focus on persons and subpopulations expected to experience significant improvements in health status—predominantly those with serious pre-existing conditions, the elderly and/or infirm. However, drawing inferences about preference changes among these subpopulations seems especially ill-advised. Even where beneficiaries are working adults, and inferences about preference changes are less troublesome, any preference changes resulting from minor or subtle improvements in health status would be expected to also be minor or subtle, and consequently difficult or impossible to detect and measure. Furthermore, any changes in marginal utility that did occur would not be restricted to environmental goods such as outdoor activities.

Moreover, improvements in health status could increase the marginal utility of consuming myriad other goods and services. Among these other goods and services are other forms of medical care. To see why, suppose that persons who experience large improvements in health status from air pollution reduction are precisely aware of how much their medical expenditures are reduced. It does not necessarily follow that these individuals will reallocate savings toward non-medical purposes. Improved health status subsequent to air pollution reduction could motivate individuals to allocate the savings to other medical purposes that have become more affordable. Improved health status subsequent to air pollution reduction (e.g., reduced cardiac risks) may make unrelated medical interventions (e.g., joint replacements) more cost-effective.

All this assumes that preference changes could be reliably attributed to improvements in health status resulting from air pollution control. But preference changes occur due to a host of phenomena including age, family status, income and technological change, just to name a few. It would be inappropriate to simply attribute improvements in health status to air pollution control. Finally, any effort to capture changes in preferences reliably attributable to improvements in health status resulting from air pollution control must take account of myriad economic, social, technological and cultural phenomena that also may change preferences.

Changes in relative preferences also may occur for reasons other than reductions in medical expenditures. For example, some people expend nontrivial resources to avert health risks from air pollution. The amount of averting behavior depends on risk preferences, budget constraints, relative prices of averting goods and services, and risk perceptions (which may be greater or less than best estimates of risk). As air pollution declines, fewer resources would be expended on averting behavior, provided that risk perceptions also decline in accordance with lowered risk estimates. In the same way, EPA representations of health risk also have effects on risk perception that, in turn, affect averting behavior and the realization of health risk.

Stepping back from the specific question posed in the charge, we are interested in seeing the assembled evidence supporting the notion that improvements in air quality, especially but not exclusively at the margin, do in fact change preferences. Except in unusual cases, preference changes reliably attributable to pollution control-mediated improvements in health status seem likely to be too small to have a material effect on benefit estimates. Pollution control-mediated improvements in health status would have to be linked to those persons or subpopulations actually expected to capture substantial improvements in health status. According to EPA's Second Section 812 Prospective, substantial improvements in health status (e.g., prevented premature mortality) are expected to be realized predominantly among those who are elderly, infirm or both (US EPA 2010). Isolating cross effects from improved health status to other goods and services among these subpopulations would require an exceptionally rich and carefully validated dataset—one also capable of showing the pathways through which these changes would be mediated.

Reiterating what we noted above, it would be helpful for EPA to assemble the available empirical evidence for preference changes reliably attributable to improvements in health status from air pollution control before proceeding further. Without such evidence, incorporating preference changes in a CGE framework would be indistinguishable from adding a new modeling assumption, and thus would add complexity without insight.

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

In the Second Section 812 Prospective, aggregate effects attributable to reduced medical expenditures resulting from air pollution control-mediated improvements in health status were calculated by extrapolating from published cost-of-illness estimates. These *cost* estimates were then interpreted as tangible *cost savings* resulting from air pollution control, with the amounts used as inputs in EMPAX-CGE. The charge asks us to consider whether this approach can be improved upon if CGE modeling proves intractable or otherwise inappropriate.

The charge question appears to presume that the approach taken in the Second Section 812 Prospective has been validated, at least as a first approximation. That presumably would have been done by the Advisory Council on Clean Air Compliance Analysis (US EPA Advisory Council on Clean Air Compliance Analysis 2010a, 2010b, 2010c, 2010d, 2010e, 2010). However, the Council's review does not seem to have addressed this specific issue.

Validity might be reasonably inferred anyway, at least as a first approximation, if significant effort had been devoted to pre-dissemination information quality review to ensure that applicable data quality standards were met, as required by government-wide and EPA guidance (Office of Management and Budget 2002; US EPA 2002, 2003), However, both the Second Section 812 Prospective and the Council's review are silent with respect to information quality. Absence from the Council's review is not surprising. It was not included in the Council's charge, as expected under government-wide peer review guidance by the Office of Management and Budget (OMB 2005).

For these reasons, an obvious way to improve upon the method in the Second Section 812 Prospective is to return to first principles and conduct a proper information quality review. This should be done before attempting to extend this model, or applying it in other circumstances.

Benefits Question 8 (B8)
Lead: Bui

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 partial equilibrium models. The current state of the literature is such that there is not enough information about either the direct or indirect benefits that may exist. An important role that EPA may play would be to encourage and support both the collection and analysis of data to improve 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.

Given the shortcomings in current understanding of these issues, we do not advocate for the inclusion of productivity gains of the workforce in any CGE or partial equilibrium modeling, or in any cost-benefit-analysis, at this time.

Benefits Question 9 (B9)
Lead: Smith

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

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

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

The details of implementing this logic have been outlined in theoretical and empirical terms.[10] Thus the process is understood and well vetted. When we introduce a measure of pollution or air

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

quality (say Q) into a structural model capable of describing a general equilibrium (such as a CGE model) it might be introduced into the representative agent's utility function as:

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

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

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

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

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

Since $\pi \cdot (Q_1 - Q_0)$ is derived from the utility function used in the model, if we set this equal to our measures for the economic value a person would place on $(Q_1 - Q_0)$ from partial equilibrium damage functions or other approaches we are implicitly applying something like the non-market equivalent of Irving Fisher's factor reversal test.[11]

Espinosa and Smith (1995) described how it might be done for the case of perfect substitution which underlies everything the strategy that EPA adopted in their CGE analysis in the Second Prospective Report (in Chapter 8) and the Mayeres and Van Regemorter (2008) work cited by EPA (2015a). However, the Espinosa-Smith work (summarizing Espinosa's (1996) thesis) incorporated all the feedbacks and the emission process. It did not adopt the "soft link" strategy of recent work.

Nonuse values by definition do not leave a "behavioral trail" or imply non-separability. There are a variety of strategies for considering their inclusion. Carbone and Smith (2013) suggest one which relaxes the full non-separability assumption[12].

There are at least two issues with incorporating nonuse values. The first is discussed in Carbone and Smith (2013) concerning whether separability of the nonuse services is the only way to represent the effects of nonuse related motives for valuing the environment. This paper argues that "faint" behavioral traits might also capture what is intended by nonuse value. A second issue

[11] Indexes for aggregates of goods using their prices or quantities need to produce some expenditures as sum of the disaggregate expenditures. See Allen (1975).
[12] See Herriges, Kling and Phaneuf (2004) for discussion of the challenges in using revealed preference information to estimate nonuse values

relevant to incorporating them in CGE models is the "extent of the market" for nonuse values. That is, what fraction of the households in a given area (or economy) have positive nonuse values? The answer to this question is especially important for aggregate analysis because it determines the income (or expenditure) share used in calibration.

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

Benefits Question 10 (B10)
Lead: Smith

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

When the benefits (or dis-benefits) of the air regulations are introduced in the models with the added assumptions that they are due to non-separable services affecting preferences, production relationships, or both, then these added connections require the "accounting framework" to be reconciled with the benefit measures. Moreover, if the links between emissions and these non-market services are also included then there is a further level of consistency to be maintained between the representation of economy-wide market outcomes and the benefit measures assigned to air regulations. If the benefit measures are incomplete, full consistency will not be achieved. However, this does not imply that such a model lacks informational value. It can offer an important plausibility gauge and can serve as a basis for evaluating whether the general equilibrium effects of major rules are important enough to warrant modifying benefit-cost estimates developed using partial equilibrium methods.

Benefits Question 11 (B11)
Lead: Fox

Charge Question B11: 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 the EPA (2015b) that, at a local or regional level, spatial sorting of heterogeneous households can have an important impact on the estimated benefits from improved air quality. Therefore the first order of business is to capture these effects in the bottom-up estimates of benefits. This also raises the question whether such spatial sorting requires a general equilibrium analysis. We think it is fair to assume that changes in commuting behavior, wages and labor supply will be most strongly felt at the local level. At a national, or even state, scale, such spatial sorting is expected to have little impact on (e.g.) national labor supply. In the interest of prioritizing resources, we would suggest that spatial sorting should be addressed in local/regional CGE modeling. This means that it plays a role in distributional analysis, but likely will not influence national benefit-cost calculations.

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

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

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

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

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

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

References

Allen, R.G.D.,1975. Index Numbers in Theory and Practice (Chicago: Aldine Publishing Co.).

Ayres, R.V., and A.V. Kneese. 1969. "Production, Consumption and Externalities". American Economic Review 59(3): 282-97.

Bell, M., Morgenstern, R., & Harrington, W. (2011). Quantifying the Human Health Benefits of Air Pollution Policies: Review of Recent Studies and new Directions in Accountability Research. Environmental Science & Policy, 14(4), 357-368.

Bieri, David S., Nicolai V. Kuminoff, and Jaren C. Pope, 2014. "National Expenditures on Local Amenities." Working Paper.

Burtraw, D., Krupnick, A., Palmer, K., Paul, A., Toman, M., & Bloyd, C. (2003). Ancillary Benefits of Reduced Air Pollution in the US from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector. Journal of Environmental Economics and Management, 45(3), 650-673.

Carbone, Jared and V. Kerry Smith, 2008. "Evaluating Policy Interventions with General Equilibrium Externalities," Journal of Public Economics, 92 (5-6): 1254-1274.

Carbone, Jared and V. Kerry Smith, 2013. "Valuing Nature in a General Equilibrium." Journal of Environmental Economics and Management, 66 (1): 72-89.

Carbone, Jared and V. Kerry Smith, 2013. "Valuing Nature in a General Equilibrium." Journal of Environmental Economics and Management, 66 (1): 72-89.

Carbone, Jared, 2005. "Calibrating Nonseparable General Equilibrium Models. Unpublished working paper, CENREP, North Carolina State University, March.

Carbone, Jared, 2005. "Calibrating Nonseparable General Equilibrium Models. Unpublished working paper, CENREP, North Carolina State University, March.

Carson, Richard T., 2011. Contingent Valuation: A Comprehensive Bibliography and History (Northampton, MA: Edward Elgar).

Chay, Kenneth Y. and Michael Greenstone, 2005. "Does Air Quality Matter? Evidence from the Housing Market," Journal of Political Economy, 113(2): 376-424.

Chetty, Raj. 2006. "A Bound on Risk Aversion Using Labor Supply Elasticities." American Economic Review, Forthcoming, NBER Working Paper No. 12067, March.

Cornes, Richard, 1980. "External effects: an alternative formulation." European Economic Review, 14 (3): 307–321.

Cornes, Richard, 1980. "External effects: an alternative formulation." European Economic Review, 14 (3): 307–321.

Davis, S. J., & Wachter, T. V. (2011). Recessions and the Costs of Job Loss. Washington, DC: Brookings Institution, Brookings Papers on Economic Activity. Retrieved from http://www.brookings.edu/about/projects/bpea/papers/2011/recessions-costs-job-loss

de Mooij, Ruud A., 2000. Environmental Taxation and the Double Dividend. North Holland, Amsterdam.

de Mooij, Ruud A., 2000. Environmental Taxation and the Double Dividend. North Holland, Amsterdam.

Diamond, Peter A., Mirrlees, James A., 1973. "Aggregate production with consumption externalities." Quarterly Journal of Economics, 87 (1): 1–24.

Diamond, Peter A., Mirrlees, James A., 1973. "Aggregate production with consumption externalities." Quarterly Journal of Economics, 87 (1): 1–24.

Edelberg, W. (2015). Dynamic Scoring at CBO (Slide Presentation). Retrieved from https://www.cbo.gov/publication/50919

Espinosa, Juan Andres and V. Kerry Smith, 1995. "Measuring the Environmental Consequences of Trade Policy: A Non-Market CGE Analysis." American Journal of Agricultural Economics, 77 (3): 772-777.

Espinosa, Juan Andres, 1996. "Consistent General Equilibrium Measurement of the Net Benefits for Improving Environmental Quality: A Computable General Equilibrium Analysis of the European Community." Ph.D. Dissertation, North Carolina State University.

Freeman, A. Myrick, III. 1982. Air and Water Pollution Control: A Benefit-Cost Assessment. (New York, John Wiley & Sons).

Giesecke, J. and J. Madden. 2013. "Regional Computable General Equilibrium Modeling" in P. Dixon and D.W. Jorgenson (eds.), Handbook of Computable General Equilibrium Modeling, Vol. 1A. Amsterdam: Elsevier.

Gollier, C. and M. L. Weitzman. 2010. "How Should the Distant Future Be Discounted When Discount Rates are Uncertain?" Economic Letters, 107(3): 350-353.

Hall, Robert F. and Charles E. Jones. 2007. "The Value of Life and the Rise in Health Spending" The Quarterly Journal of Economics, 122(1): 39-72.

Harberger, A. (1964, May). The Measurement of Waste. American Economic Review Papers & Proceedings, 54, 58-76.

Herriges, J.A., C.L. Kling, and D.J. Phaneuf. 2004. "What's the Use? Welfare Estimates from Revealed Preference Models when Weak Complementarity Doesn't Hold," Journal of Environmental Economics and Management, 47(1): 55-70.

Herriges, J.A., C.L. Kling, and D.J. Phaneuf. 2004. "What's the Use? Welfare Estimates from Revealed Preference Models when Weak Complementarity Doesn't Hold," *Journal of Environmental Economics and Management*, 47(1): 55-70.

Hertel, T.W., D.K. Lanclos, K.R. Pearson and P.K. Swaminathan. 1997. "Aggregation and Computation of Equilibrium Elasticities", chapter 3 in T.W. Hertel (ed.) *Global Trasde Analysis: Modeling and Applications*, New York: Cambridge University Press.

Hicks, J. (1939). Value and Capital. Oxford: Clarendon Press.

Holland, M., Berry, J., & Forster, D. (1998). ExternE, Externalities of Energy. European Commission, Director-General XII, Luxembourg.

Jorgenson, D.W. and P.J. Wilcoxen. 1990. "Environmental Regulation and U.S. Economic Growth," *The Rand Journal of Economics*, 21(2), pp. 314-340, Summer.

Jorgenson, D.W., R.J. Goettle, M.W. Ho and P.J. Wilcoxen. 2013a, *Double Dividend: Environmental Taxes and Fiscal Reform*, MIT Press.

Jorgenson, D.W., H. Jin, D.T. Slesnick and P.J. Wilcoxen. 2013b. "An Econometric Approach to General Equilibrium Modeling," in P.B. Dixon and D.W. Jorgenson (eds), *Handbook of Computable General Equilibrium Modeling*, Amsterdam: North-Holland, pp. 1133-1212.

Kiuila, O., & Rutherford, T. (2013). The cost of reducing CO2 emissions: Integrating abatement technologies into economic modeling. Ecological Economics, 87, 62-71.

Krewski, D., Jerrett, M., Burnett, R., Ma, R., Hughes, R., Shi, Y., . . . Tempalski, B. (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. Boston, MA: Health Effects Institute. Retrieved from http://pubs.healtheffects.org/view.php?id=315

Kuminoff, Nicolai V. and Jaren C. Pope, 2014. "Do 'Capitalization Effects' for Public Goods Reveal the Public's Willingness to Pay?" *International Economic Review*, 55(4): 1227-1250.

Lepeule, j. L., Dockery, D., & Schwartz, J. (2012). Chronic Exposure to Fine Particles and Mortality: An Extended Follow-up of the Harvard Six Cities Study from 1974 to 2009. Environmental Health Perspectives, 120(7), 965-970.

Liu, J., T.W. Hertel, and F. Taheripour. 2015. "Analyzing Water Scarcity in Global CGE Models", Water Economics and Policy (forthcoming).

Liu, J., T.W. Hertel, F. Taheripour, T. Zhu and C. Ringler. 2014. "International trade buffers the impact of future irrigation shortfalls", Global Environmental Change 29:22-31.

Mas-Colell, A., & Green, M. D. (1995). Microeconomic Theory. New York: Oxford University Press.

Matus, K., Yang, T., Paltsev, S., Reilly, J., & Name, K.-M. (2008). Toward Integrated Assessment of Envirionmental Change: Air Pollution Health Effects in the USA. Climatic Change, 88(1), 59-92.

Matus, Kira, Trent Yang, Sergey Paltsev, John Reilly, and Kyung-Min Nam, 2008. "Toward Integrated Assessment of Environmental Change: Air Pollution Health Effects in the USA." *Climatic Change*, 88 (1): 59-92.

Matus, K., K.-M. Nam, N. Selin, L. Lamsal, J. Reilly, and S. Paltsev, 2012. "Health Damages from Air Pollution in China." *Global Environmental Change*, 22(1), 55-66.

Mayeres, Inge and D. Van Regemorter, 2008. "Modeling the Health Related Benefits of Environmental Policies and Their Feedback Effects: A CGE Analysis for the EU Countries with GEM-E3," The Energy Journal, 29 (1): 135-150.

McKibbin, W.J. and P.J. Wilcoxen. 1999. "The Theoretical and Empirical Structure of the G-Cubed Model," Economic Modelling, 16(1999), pp. 123-148.

McKibbin, W.J. and P.J. Wilcoxen. 2013. "A Global Approach to Energy and Environment: The G-Cubed Model," in P.B. Dixon and D.W. Jorgenson, (eds), Handbook of Computational General Equilibrium Modeling, Amsterdam: North-Holland, pp. 995-1068.

Murphy, K. M., & Topel, R. H. (2006). The Value of Health and Longevity. Journal of Political Economy, 114(5), 871-904.

Nam, K.-M., N. Selin, J. Reilly, and S. Paltsev, 2010. "Measuring Welfare Loss Caused by Air Pollution in Europe: A CGE Analysis." Energy Policy, 38(9), 5059-5071.

Noll, Roger and Trijonis, John, (1971), Mass Balance, General Equilibrium, and Environmental Externalities, American Economic Review, 61, issue 4, p. 730-35.

OMB (2002). Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies; Notice; Republication. Federal Register 67:8452-8460. Available at: https://www.whitehouse.gov/sites/default/files/omb/fedreg/reproducible2.pdf.

OMB (2005). Final Information Quality Bulletin for Peer Review. Federal Register 70:2664-2667. Available at: https://www.gpo.gov/fdsys/granule/FR-2005-01-14/05-769.

Pelikan, J. W. (2015). Green light for green agricultural policies? An analysis at regional and global scales. Journal of Agricultural Economics, 66(1), 1-19.

Pelikan, J., Britz, W., & Hertel, T. (2015). Green light for green agricultural policies? An analysis at regional and global scales. Journal of Agricultural Economics, 66(1), 1-19.

Perroni, Carlo, 1992. “Homothetic Representations of Regular Non-Homothetic Preferences.” Economic Letters, 40 (1): 19-22.

Perroni, Carlo, 1992. “Homothetic Representations of Regular Non-Homothetic Preferences.” Economic Letters, 40 (1): 19-22.

Peters, J. (2015). Electric Power and the Global Economy: Advances in Database Construction and Sector Representation. Doctoral Dissertation, Purdue University.

Pope, C., Burnett, R., Thun, M., Calle, E., Krewski, D., Ito, K., & Thurston, G. (2002). Lung Cancer, Cardiopulmonary mortality and long-term exposure to fine particulate air pollution. Journal of the American Medical Association, 287(9), 1132-1141.

Rogerson, Richard, 2015. “ A Macroeconomic Perspective on Evaluating Environmental Regulations.” Review of Environmental Economics and Policy, 9(2):219-238.

Rose, A. and G. Oladosu. (2002). Greenhouse Gas Reduction Policy in the United States: Identifying Winners and Losers in an Expanded permit Trading System. Energy Journal, 23(1), 1-18.

Rutherford, Thomas F., 2002. “Lecture Notes on Constant Elasticity Forms.” Unpublished paper. Boulder: University of Colorado, November.

Rutherford, Thomas F., 2002. “Lecture Notes on Constant Elasticity Forms.” Unpublished paper. Boulder: University of Colorado, November.

Saari, R., Selin, N., Rausch, S., & Thompson, T. (2015). A self-consistent method to assess air quality co-benefits from US climate policies. Journal of Air and Waste Management Association, 65(1), 74-89.

Sandmo, Agnar, 1980. “Anomaly and stability in the theory of externalities.” Quarterly Journal of Economics, 94 (4): 799–807.

Schwartz, Jesse, and Robert Repetto, 2000. “Nonseparable utility and the double dividend debate: re-considering the tax-interaction effect.” Environmental and Resource Economics, 15 (2): 149–157.

Sieg, Holger, V. Kerry Smith, H. Spencer Banzhaf, and Randy Walsh, 2004. "Estimating the General Equilibrium Benefits of Large Changes in Spatially Delineated Public Goods." International Economic Review, 45(4): 1047-77.

Smith, V. Kerry, 2015. “Should Benefit Cost Analyses Take Account of High Unemployment? Symposium Introduction” Review of Environmental Economics and Policy, 9 (2):165-178.

Smith, V. Kerry and J. Andres Espinosa, 1996. “Environmental and Trade Policies: Some Methodological Lessons” Environment and Development and Economics, 1(1):19-40.

Smith, V. Kerry and J. C. Huang, 1995. "Can Markets Value Air Quality? A Meta-Analysis of Hedonic Property Values Models." Journal of Political Economy, 113(2): 209-227

Smith, V. Kerry, G. L. Van Houtven, and S. K. Pattanayak. 2002. "Benefit Transfer via Preference Calibration: 'Prudential Algebra' for Policy." Land Economics, 78(1), 132-152.

Smith, V. Kerry, S. K. Pattanayak, and G. L. Van Houtven. 2003 "VSL Reconsidered: What Do Labor Supply Estimates Reveal About Risk Preferences?" Economics Letters, 80(2):147-153.

Smith, V. Kerry, S. K. Pattanayak, and G. L. Van Houtven. 2006. "Structural benefit transfer: An example using VSL estimates." Ecological Economics, 60(2), 361-371.

Stevens, A.H, D.L. Miller, M.E. Page and M. Filipski. 2015. "The Best of Times, the Worst of Times: Understanding Pro-cyclical Mortality," American Economic Journal: Economic Policy, 7(4): 279-311.

Sue Wing, I. (2006). The Synthesis of Bottom-up andTop-down approaches to climate policy modeling: electric power technologies and the cost of limiting U.S. CO2 emissions. Energy Policy, 34, 3847-3869.

Sue Wing, I. (2008). The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Economics, 30, 547-573.

TERM-USA Model. 2013. Center of Policy Studies (CoPS), Victoria University, Australia.

U.S. Environmental Protection Agency, Office of Air and Radiation, The Benefits and Costs of the Clean Air Act from 1990 to 2020 Final Report – Rev. A April 2011

U.S. 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 (August 2010)..EPA-COUNCIL-11-001. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/9288428b8eeea4c885257242006935a3/1E6218DE3BFF682E852577FB005D46F1/$File/EPA-COUNCIL-11-001-unsigned.pdf

U.S. EPA (2002). Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency (EPA/260R-02-008).

U.S. EPA (2003). A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information. A Report of the EPA Science Policy Council. Available at http://www.epa.gov/sites/production/files/2015-01/documents/assess2.pdf.

U.S. EPA (2011). The Benefits and Costs of the Clean Air Act from 1990 to 2020; Final Report – Rev. A. Available at: http://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-report-documents-and-graphics.

U.S. EPA Advisory Council on Clean Air Compliance Analysis (2010a). Review of Revised PM2.5 Emissions and Modeling Estimates for the Second Prospective Study of Benefits and Costs of the Clean Air Act. EPA-COUNCIL-10-005. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/WebReportsLastFiveCOUNCIL/24371796451D6E008525779F0073C22E/$File/EPA-COUNCIL-10-005-unsigned.pdf.

U.S. EPA Advisory Council on Clean Air Compliance Analysis (2010b). Advisory on a Preliminary Draft of the Second Section 812 Prospective Study of the Benefits and Costs of the Clean Air Act (April 2010). EPA-COUNCIL-10-004. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/9288428b8eeea4c885257242006935a3/553D59A280CDCF388525776D005EE83A/$File/EPA-COUNCIL-10-004-unsigned.pdf

U.S. EPA Advisory Council on Clean Air Compliance Analysis (2010c). Review of Ecological Effects for the Second Section 812 Prospective Study of Benefits and Costs of the Clean Air Act. EPA-COUNCIL-10-003. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/WebReportsLastFiveCOUNCIL/19D10CA154BC205485257745007D791D/$File/EPA-COUNCIL-10-003-unsigned.pdf .

U.S. EPA Advisory Council on Clean Air Compliance Analysis (2010e). Review of EPA's DRAFT Health Benefits of the Second Section 812 Prospective Study of the Clean Air Act. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/0/72D4EFA39E48CDB28525774500738776/$File/EPA-COUNCIL-10-001-unsigned.pdf.

U.S. EPA. 2010f. Valuing Mortality Risk Reductions for Environmental Policy: A White Paper. Available at: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0563-1.pdf/$file/EE-0563-1.pdf

U.S. EPA. (1999). The Benefits and Costs of the Clean Air Act: 1990 - 2010. EPA Report to Congress, United States Environmental Protection Agency. Retrieved from http://yosemite.epa.gov/ee/epa/eerm.nsf/vwRepNumLookup/EE-0295A?OpenDocument

U.S.EPA Advisory Council on Clean Air Compliance Analysis (2010d). Review of Air Quality Modeling for the Second Section 812 Prospective Study of Benefits and Costs of the Clean Air Act. EPA-COUNCIL-10-002. Available at: http://yosemite.epa.gov/sab%5Csabproduct.nsf/F30DE02361BBD06C852577450077AAB2/$File/EPA-COUNCIL-10-002-unsigned.pdf.

US EPA (2015a). Economy-Wide Modeling: Social Costs and Welfare White Paper. Prepared for the U.S. EPA Science Advisory Board Panel on Economy-Wide Modeling. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/a84bfee16cc358ad85256ccd006b0b4b/7f1209feb69099ec85257dfd00605b67!OpenDocument&Date=2015-10-22.

U.S. EPA (2015b) Economy-Wide Modeling: Benefits of Air Quality Improvements White Paper. Prepared fo the U.S. EPA Science Advisory Board Panel on Economy-Wide Modeling. Available at: http://yosemite.epa.gov/sab/sabproduct.nsf/a84bfee16cc358ad85256ccd006b0b4b/7f1209feb69099ec85257dfd00605b67!OpenDocument&Date=2015-10-22.

Vrontisi, Zoi, Jan Abrell, Frederik Neuwahl, Bert Saveyn and Fabian Wagner, 2016. "Economic Impacts of EU Clean Air Policies Assessed in a CGE Framework." Environmental Science and Policy, 55 (1): 54-64.

Weitzman, M. L. 1998. "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate." Journal of Environmental Economics and Management, 36: 201-208.

Williams III, Roberton C., 2002. "Environmental tax interactions when pollution affects health or productivity." Journal of Environmental Economics and Management, 44 (2): 261–270.

Williams III, Roberton C., 2002. "Environmental tax interactions when pollution affects health or productivity." Journal of Environmental Economics and Management, 44 (2): 261–270.

Williams III, Roberton C., 2003. "Health effects and optimal environmental taxes." Journal of Public Economics, 87 (2): 323–335.

Williams III, Roberton C., 2003. "Health effects and optimal environmental taxes." Journal of Public Economics, 87 (2): 323–335.

Yang, T., Matus, K., Paltsev, S., & Reilly, J. (2004). Economic Benefits of Air Pollution Regulation in USA: An Integrated Approach. Report 113, Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA. Retrieved from http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt113.pdf