NBER WORKING PAPER SERIES

EVALUATING ECONOMY-WIDE BENEFIT COST ANALYSES

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Working Paper 22769
http://www.nber.org/papers/w22769

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
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October 2016

Thanks are due Berthold Herrendorf and Christos Makridis constructive suggestions and comments on the research design. Neither is responsible for any errors associated with the research. Thanks are also due to Shauna Mortensen for preparing multiple drafts of this paper. An early version of this research was presented by the first author at the Conference of the Danish Environmental Economics Council 2015. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 22769
October 2016
JEL No. D58,D61,H41

ABSTRACT

This paper examines a new strategy for evaluating whether the size of a new environmental regulation requires that benefit cost analyses consider general equilibrium effects. Size in the context refers to both the magnitude and distribution of cost increases across sectors and the benefits attributed to the rules. Rogerson’s [2008] static, general equilibrium model describing how tax policy affects time allocations between market and non-market activities is extended to include air pollution as a non-separable element in the representative household’s preferences. The paper makes three contributions to the literature. First, the calibrated parameters of the model are used to evaluate how the introduction of air quality, as a non-separable, external influence on the household’s non-market activities, affects the conventional explanation for the labor market transition in developed economies. Second, all current CGE assessments of conventional environmental policies in the U.S. and Europe ignore the feedback effects of policies for emissions and behavior. This analysis demonstrates their importance by using an amended version of the Rogerson model to compare calibrations with and without these feedback effects. Finally, a calibrated model is used to gauge the plausibility of the benefit estimates from EPA’s partial equilibrium (PE) assessment of the recent Clean Power Plan. This analysis finds the upper limit of the PE estimates for the annual ancillary benefits of the plan (due to its effects on conventional air pollutants) is implausibly large.

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I. Introduction

Benefit cost analysis was never intended to be used for evaluating policies large enough to have impacts at an economy wide basis. There have been a number of efforts to gauge the general equilibrium effects of large policies in settings roughly consistent with benefit cost assessments[1]. The Hazilla-Kopp [1990] analysis of the social costs of environmental regulations, for example, found the relationship between social and engineering costs changed with increasing regulation. Their comparison, based on 1981 estimates, found engineering costs were fifty percent larger than social costs, while in 1990 the relationship reversed with engineering costs sixty percent less than the social costs. They did not consider the beneficial effects of the policies involved.

One of the most dramatic recent illustrations of the importance of the details associated with introducing the beneficial effects of environmental policy can be found in EPA's Second Prospective study [2011] of the net benefits of the 1990 Clean Air Act Amendments (CAAA). This analysis compared the benefit estimates derived using their conventional partial equilibrium (PE) approach with those computed using a large scale CGE model (EMPAX CGE, see ICF Inc. [2010]) adapted to reflect the "with" and "without" CAAA policies. The annual net benefit estimates in 2010 based on PE methods were 109 times larger than the CGE benefit measures.

[1] Kokoski and Smith [1987] and Hazilla and Kopp [1990] were the first to our knowledge to use computable general equilibrium (CGE) models to assess the importance of general equilibrium effects for benefit cost analyses.

The former were estimated to be 1.2 trillion dollars, about 8.0% of the estimates for 2010 GDP.[2] Little was done to attempt to explain the sources for the differences. To some degree, this is understandable. The EMPAX CGE model is a complex, multi-sector model. There are five energy sectors, agriculture, mining (excluding coal, crude oil or natural gas), construction, nineteen manufacturing sectors, and eight service sectors. There are four representative households classified by income class within each of five regions. Preferences are represented as nested CES functions. Production is also specified as nested CES functions (see ICF Inc. [2010] for details). This model has many moving parts, all contributing to its general equilibrium (GE) outcomes. EPA's analysis of the 1990 CAAA introduces the effects of the amendments as differences in the labor endowment for the "with" rules (i.e. labor available because of the "avoided" deaths in expected value terms) compared to the "without" case along with the difference in medical expenditures in the two situations. Identifying one or more sources for the differences in relationship to the assumptions of EPA's PE analysis would be exceptionally difficult.[3]

Emissions of air pollutants are *not* part of the EMPAX model. As a result there are no feedback effects of policy. In a model specified to include these feedbacks, air pollution would be recognized as affecting the economic activities of households and firms. Their responses, in turn, changes the goods and services consumed, time allocations between work and leisure, and as a result pollution emissions. Non-market outcomes are then a part of the general equilibrium

[2] These estimates are for 2010 as reported in Table 8.8 They are in 2006 dollars. The PE benefits are $1.3 trillion. Because the CGE estimates include both the increases in labor endowment and reductions in medical expenditures contributed to the policy plus the estimated compliance costs, only the net benefits are comparable.

[3] The PE and CGE analysis are discussed as adopting alternative approaches to defining benefits with the CGE based on a human capital approach. It used the additions to the time endowment due to avoided mortality and awarded such days, as well as reduced medical expenditures.

EPA's assessment [2015a, pp 17-19] of the potential limitations also noted that mortality and morbidity effects for individuals outside the labor force were excluded.

and the full story under these conditions is likely to be more nuanced.[4] None of the analyses of existing policies whether in the U.S. or Europe allows one to evaluate if feedback effects account for these types of differences in benefit measures using PE versus GE perspectives.[5]

We outline a new strategy for evaluating whether the size of a new rule requires that benefit cost analyses consider general equilibrium effects by adapting Rogerson's [2008] model to include air pollution. His model focuses on how macro policy affects time allocations between market and non-market activities. As a result, it is well suited to our needs. Using the calibration practices common in macro-economics, we make three contributions to this literature. First, we use the calibrated parameters to evaluate how the introduction of air quality, as a non-separable, external influence on the household's non-market activities affects the conventional explanation for the labor market transition in developed economies.[6] This approach allows us to also assess the impact of the "importance" we assign the environmental services. We find it does not overturn the strong substitution between market goods and a composite of market and household services. Second, we compare calibrations with and without feedback effects. Our results imply that the use of soft links (or omitting feedbacks) is nearly equivalent to ignoring the role of environmental services in the household's preferences. When the calibrated parameters from the model with air quality, ignoring feedbacks, are used in Rogerson's original specification that omits environment, the predictions of time allocations are generally better than those derived using the calibrated parameters derived with feedbacks. This conclusion is reversed when we use

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[4] See Carbone and Smith [2008] for discussion of the implications of non-separable air quality for the calibration of traditional CGE models and for the measurement of the excess burden of taxes.

[5] Based on private correspondence with John Riley of the MIT Emissions Prediction and Policy Analysis Model (EPPA) and Bert Saveyn and Michael Holland for GEM-E3 for Europe, these other CGE models do not include emissions and diffusion of pollution within the respective models. The effects of pollution are computed outside these models and components of each model adjusted. As a result, there are not feedbacks and the associated joint determination of outcome for the general equilibrium solutions. See Matus et al. [2008] for discussion of EPPA and Vrontisi et al. [2006] for the GEM-E3 model.

[6] The effect is characterized as external because air pollution affects the representative agents' tradeoffs for market goods and services as well as time allocations inside and outside the market but it is not a choice variable.

these calibrations in the expanded model with all the parameters, including those for environmental quality. In this case the calibration with feedbacks is clearly preferred. Finally, we demonstrate how our calibrated model can be used to gauge the plausibility of the benefit estimates from new PE policy assessments. To illustrate this new role, we use a stylized version of EPA's recent Clean Power Plan and find the upper limit of the PE estimates for annual ancillary benefits of the plan (due to its effects on conventional air pollutants) would be judged as implausibly large using our preferred calibrated model.

Section II outlines the motivation for our proposed approach for evaluating PE benefit cost analyses. Section III summarizes the main components of Rogerson's model and our additions to it. Section IV presents the calibration results and describes how our calibration helps to isolate what should be measured as part of taking account of non-market environmental services. Section V describes the effects of "soft links" versus a full feedback structure. Section VI summarizes how we analyze the Clean Power Plan, and the last section discusses why our proposed strategy is important to other proposed reforms to the design of regulations.

II. Context

In April 2015 the World Health Organization reported that conventional air pollutants were "costing" Europeans $1.6 trillion U.S. dollars (in 2010).[7] If the assessment is limited to those households in the EU, the estimate amounts to about 8% of the EU's GDP. As noted at the outset, the 1990 Clean Air Act Amendments were estimated to "save" U.S. households about $1.3 trillion dollars in gross benefits annually, nearly 9% of U.S. GDP (in 2010).[8] More recently, EPA's Clean Power Plan intended to reduce CO_2 in response to concerns about climate change,

[7] The WHO Regional Office for Europe, OECD [2015] prepared the analysis.
[8] Our earlier comparison used net benefits (PE benefits less costs) because this was what would be comparable to the CGE estimates.

was found to be "worth doing" *because of the ancillary benefits alone!* The gains attributed to reductions in conventional pollutants would be between $14 and 34 billion a year (in 2011 dollars) when mandates are fully met (in 2030).[9] The newest EPA proposal—a more stringent standard for ozone of 70 ppb (EPA [2015c]) is proposed to yield annual benefits of $2.9 to 5.9 billion dollars (in 2025). Sixty to seventy percent of these are co-benefits due to induced reductions in PM2.5 from the controls required to reduce ozone. The estimated magnitude for benefits or co-benefits in each of these cases is not the result of double counting. These EPA assessments are careful to document exactly what is assumed about the other rules in computing the baselines for measuring the additional gains associated with each new rule.

All these assessments use a common method for measuring the benefits from the specified reductions in one or more air pollutants. It is a damage function approach. A statistical model is used to relate a change in a health endpoint in response to a change in the air pollution metric hypothesized to be responsible for the effect. When the endpoint is a change in mortality risk experienced by a spatially delineated sub-population, the expected cases of premature death are aggregated to estimate the national effect. The benefits of the improvement are then estimated using the value of a statistical life (VSL) as a summary measure for the tradeoff that a set of representative individuals would make to reduce risks enough to avoid one death in expected value terms.

Households and firms adjust to new rules, especially if they are significant. Analysts in EPA and the EU are increasingly recognizing that size of the benefits attributed to a new

[9] These estimates are from the final RIA (U.S. Environmental Protection Agency [2015b]). They are for the rate based approach assuming a 3% discount rate for the co-benefits and a 3% of the social costs of CO_2. They are taken from Table ES-7 in the Executive Summary of the report. They are computed as the difference between the total benefits and the climate benefits only.

regulation matters for the plausibility of the PE approach[10]. However, the general equilibrium models being used to consider multi-market effects completely leave out the inter-connections between firms and households' decisions and the generation of emissions. Instead a "soft link" is used. Estimates of health effects are computed separately with pre-specified assumptions about emissions and air quality using the conditions attributed to the cases for the policy and without it. The health expenditure changes and impacts on available labor endowment are introduced as "savings" in the "with policy" scenarios. Behavioral responses to improved quality that might alter the mix of consumption and leisure decisions are omitted because they are assumed to be "second order" effects.

One might ask: what is the threshold for a first order effect? This question has not been answered. The assessments often cite the Mayeres and Van Regemorter [2008] study as supporting the conclusion that feedbacks are of second order importance. However, these authors' analysis used a model that must yield this conclusion because it assumes there is a perfect substitution between private goods associated with health care and the labor endowment effects due to improved air quality.[11] While this issue might seem to be a matter for academic debates, questions about the plausibility of a partial equilibrium framework grow in importance as the size of the proposed policy impacts increases in relation to the economy experiencing the new rules. Moreover, the GE models used to support the plausibility of the PE methodology for large, policy-induced, changes in pollution all ignore feedbacks.[12]

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[10] In the United States, the Environmental Protection Agency's Science Advisory Board convened a panel of economists and scientists to assist the agency in improving its capability to assess economy-wide impact from the benefits and costs of its regulatory proposals. A key focus of the panel is on the technical merits and challenges in using economy wide models to analyze air regulations. See the summary in Wolverton [2015] for more details on the charge to the panel.

[11] This result was established in Espinosa [1996]. See Espinosa and Smith [1995] for a summary and Carbone and Smith [2008] for a more general assessment of the effects of non-separability.

[12] See Vrontisi et al. [2016] as another recent example.

III. Rogerson's Model Augmented with Air Quality

Rogerson's [2008] static GE framework offers a model of time allocation for households in an aggregate economy. These allocations are described as a sequence of static choices where productivity and income tax rates vary but preferences are held constant. This approach directs primary attention to the roles of income and substitution effects in determining how time is allocated between market work, home production, and leisure. As a result, it focuses on what these effects imply for economy wide responses to differences in taxes or other policies across otherwise comparable economics.

The representative household's preferences are described using a variation on the Brown-Heien [1972] S-branch utility function. Rogerson's version specifies the top level as Cobb-Douglas in consumption and leisure. Consumption is composed of one branch with market goods including a subsistence level of the produced commodities and a branch for services using a CES function that is composed of market and home produced services.[13] Labor income is taxed at a proportional rate. These tax revenues finance a lump-sum transfer to the representative household. To assure our extension is as transparent as possible, we use the same notation as in Rogerson for the elements in the model that don't change. (Appendix A summarizes all the elements in the model.)

Here we focus on the components where we introduce changes to allow for the effects of environmental services, empirically represented in our calibration and application by air quality. Equation (1) is the consumption branch of the preference function with the CES sub-function for services including those purchased in the market and those that are home produced.

[13] A common reason for using the Stone-Geary specification with a subsistence level of consumption is to assure non-unitary income elasticities. However, with quasi fixed goods, the nested CES becomes non-homothetic so this formulation would not be necessary when air quality is introduced (see Carbone and Smith [2008]). We maintain this format for the goods branch to allow comparison of the calibrated parameters with Rogerson's results.

$$(1)\quad C=\left[\alpha_G(G-\bar{G})^{\epsilon}+(1-\alpha_G)(\alpha_S S^{\eta}+(1-\alpha_S)N^{\eta})^{\frac{\epsilon}{\eta}}\right]^{\frac{1}{\epsilon}}$$

Where

C = consumption

G = market goods

$\bar{G}$ = subsistence consumption of market goods

S = market services

N = household produced services

Market goods and services as well as home production are the result of fixed coefficient technologies based on labor allocated to each activity (H_i designating the labor time with $i = G,\ S$ and N for each sector), as in equation (2).

$$(2)\quad G = A_G H_G,\ \mathrm{S} = A_S H_S,\ N = A_N H_N$$

The labor productivities (the A_i's) change over time, each at a different exogenous rate. The wage is normalized to unity so the equilibrium prices for market goods are given in equation (3).

$$(3)\quad P_G = \frac{1}{A_G},\ \ P_S = \frac{1}{A_S}$$

Leisure (H_L) is the residual from time allocated to market activity (for producing G and S) and home production (N). Total time is normalized to unity. Leisure (H_L) is defined in equation (4).[14]

$$(4)\quad H_L = 1 - H_G - H_S - H_N$$

Our extension maintains the focus on the representative household's time allocation because environmental services are likely to be experienced through differences in how time is used. We

[14] Rogerson does not define H_L since it is implied by other allocations and the normalization used for total time.

represent environmental services with the ambient concentration of particulate matter.[15] To include air quality we add a further nest to the service component of equation (1), replacing N with a CES function of N and Q. Q designates air quality. So the term for N in the service nest of equation (1) (designated by $F(S,N)$ in the original Rogerson model) is replaced by a function that includes N as well as a measure for ambient air quality, Q.

$$(5) \quad F(S,N,Q) = \left[\alpha_S S^{\eta} + (1-\alpha_S)(\alpha_N N^{\varphi} + (1-\alpha_N)Q^{\varphi})^{\frac{\eta}{\varphi}}\right]$$

Q is treated as quasi-fixed in the first order conditions describing the agent's choice of S and N. Thus, the level of Q influences the MRS for market and household produced services as well as that for all other choices. The feedback effect is portrayed simply as in equation (6).

$$(6) \quad Q = \frac{1}{\mu \cdot G}$$

The parameter μ reflects both the emissions produced as a result of the selected amount of G, *and* the atmospheric diffusion process for these emissions. Thus environmental services are assumed to be the inverse of the ambient concentration of pollution.

The actual air diffusion models used for policy are very complex. They represent the chemical and atmospheric processes that capture the effects of mixing of contaminants and the diffusion over space. For significant environmental rules the models and assumptions used in matching them to proposed rules are a key focus of the policy evaluation. In the Second Prospective analysis, for example, the air quality modeling was the central focus of a full chapter in the report (Chapter 4) and had implications for all the key components of the benefit

[15] We measure all air pollutants as PM10 equivalents – PM is most important air pollutant in PE health assessments. The form used to measure it has changed as the health risk assessment research has focused attention on smaller particles. PM2.5, the measure for the ambient concentration of particles 2.5 microns or smaller, is now the measure that is the primary focus for health impacts.

analysis.[16] Our model has no spatial detail. To include feedback effects between economic activity and environmental quality we embed all the assumptions about emissions and diffusion in a single parameter. Our focus here is on the *economic responses* to exogenous (to the agent) changes in air quality. Equally important, we do not include an abatement sector so policy scenarios are introduced thru changes in μ. This simplicity allows the analysis to focus on how income and substitution effects determine the importance of differences in the GE effects for large policies. Behavioral responses to different forms of regulations could be included as part of the choice of abatement methods. This strategy complicates the responses portrayed in the model and is left for future research.

The CGE models used for policy in the U.S. and Europe have so-called *soft links* between the economic process and emissions. This formulation implies the link between Q and G that allows preference related tradeoffs to change with policy is not captured by these models. This point is worth further elaboration because the strategy Rogerson used to calibrate his model selects the model's parameters to match the moments that describe the first order conditions for an optimal time allocation both between leisure and work and among market and non-market activities in two years (1950 and 2003 in his case). These conditions necessarily coordinate with selection of goods and services, given exogenous labor productivity and tax rates in each of these two years. In our application we will set the values for Q in the first of these years (1950) and then select μ based on conditions in 2005 (our second year for calibration). Q is determined endogenously in 2005 recognizing the feedback effects between G and Q as well as its impact on other tradeoffs.

[16] A detailed appendix by Douglas et al. [2008] documented the extensive modeling required.

IV. Calibration with Non-Separable Air Quality

Our objective is to offer a new approach for evaluating the plausibility of partial equilibrium benefit cost assessments. This process also allows the parameter calibration to be used as one yardstick. One aspect of that calibration arises in the assumptions made about the importance assigned to air quality thru the size of the moment associated with non-market tradeoffs. The importance of this moment can be gauged by considering how it affects the other economic parameters where we have experience to judge the values implied by each calibration. We follow Rogerson's calibration assumptions as much as possible. Table 1 summarizes his estimates for the aggregate time allocation along with the updates to these estimates from Duernecker and Herrendorf [2015] for 2005. We selected 2005 because it is a closer match to some of the sources for measures of air quality and precedes the Great Recession. We follow Rogerson and match the moments describing decisions about market versus household services, goods versus services, and goods versus leisure in two years 1950 and 2005.

Our model evaluation proceeds in steps. First, we check our logic by demonstrating our calibration reproduces his original parameter estimates. Then, we assess the effects of using 2005 instead of 2003 as well as using separate estimates for γ_N, rather than attempting to calibrate a value for this household productivity parameter. By using updated estimates for γ_N (from Duernecker and Herrendorf) we avoid the need to calibrate this parameter and can concentrate on those associated with the environmental sub-function.

We begin using these moments for 1950 and 2003. We adopt Rogerson's assumptions about average growth rates in productivity for the goods and service sectors (γ_G = 2.48 and γ_S = 1.44 respectively), along with his central estimate for the parameter describing the elasticity of substitution between home produced and market services. This implies that the parameter for the substitution η, will be .45. These moments do not include the effects of Q^{17}. In his model N is used in place of the sub-function in equation (5). His calibrated values are in the first column of Table 2 and our replication is in the second column. Next, we use Duernecker and Herrendorf's (DH) estimate for the growth rate in productivity in the home production (γ_N = 0.07) and replace 2003 with 2005.[18] The results for this calibration are given in the third column of the table.

By using the DH estimate for γ_N (and treating μ as a technical parameter that we set based on existing data for 2005) we can calibrate the parameters associated with the new "environmental" sub-function by adding one more moment. This equation conveys the information about the importance of air quality to the household. Equation (7) describes the moment in "generic" terms. To simplify the description we don't repeat the full expression for the MRS involving Q in (7) below[19].

(7) $$\frac{\frac{\frac{U_Q(Q-Q_0)}{(1-\alpha_C)}}{\left((1-\tau)H_L\right)}}{W(H_G+H_S)}$$ = Aggregate Value of Reducing PM10 equivalent of $(Q - Q_0)$ relative to pre-tax wage compensation

This equation provides one possible measure of the monetary tradeoff a household would make for a $(Q - Q_0)$ change in air quality relative to their pretax wage income. We use the marginal rate of substitution (MRS) to estimate a constant tradeoff for a marginal change in air quality that is applied to the specified non-marginal increment in air quality. This formulation is adopted

[17] They correspond to Rogerson's equations (4), (5), and (6) are also given in our appendix as (5), (6) and (7).
[18] Rogerson's calibration implies a negative productivity for home production, as reported in our Table 2 and his Table 2.
[19] Other specifications comparable to those used in Carbone and Smith [2008] would yield a different set of implicit restrictions that govern calibration.

because it is closer to the form of most empirical benefit measures than a Hicksian willingness to pay for a discrete change in air quality.[20]

The normalizations in Rogerson's model imply that estimates for most of the market related variables are introduced in relative terms. These normalizations are routine in economic models for marketed goods and services. The literature on price and quantity indexes for these goods is well established. Beginning with Irving Fisher's criteria for consistent price indexes (see Allen [1975]), one finds a documented logic for linking applied theory and empirical practice. The same is not true for the practices used in non-market valuation.[21] As a result, the definition in equation (7) plays two roles. First, it is needed to complete the calibration of the parameters of preferences associated with environmental quality, Q. Second, it assures a consistent relationship between the estimates of monetary tradeoffs for air quality from the literature and their representation in our amended version of Rogerson's model. That is, the empirical estimates for monetary tradeoffs for reductions in PM10 (i.e. the right side of equation (7)) are usually estimated for a small change and are treated as constants. By contrast, the MRS on the left side of equation (7) is evaluated at a set of values for the variables which each preference specification implies will contribute to that tradeoff. The model is best interpreted as determining relative values.

As a rule, calibration of a macro model is expected to provide an exact match of each moment. It reflects a single solution to a consistent set of equations that define how the conditions describing the economic process interact in establishing the equilibrium. This moment

[20] Nothing in our proposed method precludes the use of EV or CV measures of Hicksian surplus in framing this moment. They would require estimates for these Hicksian benefit measures that are usually not available.

[21] For market goods a key condition in defining consistent price and quantity indexes in the Fisher factor reversal test (i.e. aggregate price and quantity indexes must be consistent and yield same total expenditures for the sum of the disaggregated elements contained in the aggregate). In non-market valuation, there are different strategies for measuring the monetary tradeoffs. They imply different conceptual measures. To compare them and use them consistently, they must first be linked to a single description that describes their relationship to the tradeoff applied by individual preferences. See Smith et al. [2002].

is different. It uses the shadow value of Q to estimate an approximate benefit for a discrete change in Q as a share of income. There is nothing in the economic process that requires this condition to hold exactly. It is one measure that could be used to gauge the economic importance of air quality changes and we are requiring the model's implications for its importance to be consistent with measures from the literature. This distinction is important to interpreting the "fit" of our moments for all the variables determined by the model. Prescott's [2016] recent overview of the development of macro models for the real business cycle emphasizes how a unified theory allowing the construction of national income statistics that can be matched to existing data contributed to the progress. No doubt this symmetry in the definitions for actual statistics and their modeled counterparts helps to assure better correspondence in the calibration of these models. There is no natural correspondence for the non-market services environmental services. They are not part of national income accounts. As a result the match between the moments and market and non-market variables will now be imperfect. We use these disparities to help in signaling the importance of the assumptions about how environmental services are introduced into the model[22].

There are data limitations that affect our calibration of the nonmarket sector. The Q moment is used for 2005 and not 1950. We do not have reliable measures for the MRS for 1950. Equally important, the information needed to measure μ for 1950 is limited. Since this parameter reflects both atmospheric conditions <u>and</u> policy, we used information on emissions and ambient quality in 2005 to construct our measure for μ. Air quality is measured by the inverse of national

[22] Recently Millner and McDermott [2016] have highlighted the failure to evaluate models used for integrated economic assessments of climate policy. The role of a model's description of the climate system in relation to the process determining economic growth is important to its ability to reproduce historical records. They illustrate this point with Nordhaus'[2014] DICE model over the period 1870 to 2010. While Rogerson's model is only static, we are proposing that the comparison of the fit associated with different calibrations as well as these types predictions become a part of assessing models that attempt to link non-market services to market based economic activity. Thanks are due Pietro Perreto for raising this issue in the context of the integrated assessment models and economic growth models.

average value for PM10 in 1950 and 2005. Over this period both the measure used to characterize the ambient concentration of particulates and the statistic EPA uses to summarize concentrations over time and location have changed. The adjustments we used to develop a consistent set of measures for PM10 are summarized in Table 3.

Two different values for the non-market share of wage income are considered. The first is based on measures for the average annual concentration of PM10 in 1950 and 2005, along with estimates from a meta- analysis of hedonic property model estimates (Smith and Huang [1995]). We selected the average of the past estimates in 2005 dollars as the largest plausible value based on the hedonic property value research. This estimate is about fifty percent larger than Chay and Greenstone's [2005]. The ambient concentration of particulate matter declined over this period by 77.2 percent. This approach implies that the monetary value of this change in particulates would be about 5.4 percent of total wage compensation in 2005.[23] The second measure is larger and is based on estimates adapted from the Second Prospective analysis. This analysis compares "current" conditions with the 1990 Clean Air Act Amendments relative to a counterfactual that is intended to represent the ambient conditions "without" regulations. Using the annual benefits for 2010 (measured in 2006 dollars) as a fraction of wage compensation in 2007 (the closest year with comparable measures for wage compensation from the GGDC data base), the benefits would be 17.5 percent of total wage compensation.[24] These benefits are due to *all* the changes in criteria air pollutants the analysis attributes to the Clean Air Act. Nonetheless, reductions in particulates account for the majority reductions in mortality risk and thus most of the benefits.

[23] Using the Chay and Greenstone estimate would reduce the share to about 3.7 percent.
[24] This estimate may seem too much of a back of the envelope assessment. It is intended as an upper bound. If we were to use the EPA estimate for benefits in 2000, this amounts to 749 billion (in 2006 dollars). Relative to 2000 wage compensation (also measured in 2006 dollars) it would be 14.7 percent. We selected the larger estimate as an upper bound.

1.2 of the 1.3 trillion dollars in benefits for 2010 are due to reductions in mortality risk for adults 30 and older as a result of the reductions in particulate matter.

The EPA report provides very detailed maps documenting the spatial impact of the emission changes for ambient air quality conditions. Our analysis requires two numbers summarizing the ambient conditions for the U.S. as a whole. These measures are intended to describe levels of particulate matter for the “with” and “without” conditions. We use the population weighted average of the changes in PM10 for New York, Chicago, Los Angeles, and Pittsburgh to approximate the reduction.[25] This estimate implies a 55.3 percent reduction in PM10 based on comparing the “with” CAAA to without estimates. Thus, the EPA health effects approach to valuing air quality attributes a larger monetary value to a smaller proportionate improvement in air quality than with the first calibration.

One way to compare this estimate with the lower share is to compute the implied household marginal willingness to pay for particulate matter. To develop this measure we use the same number of households as was assumed for the lower estimate for the Q-share (i.e.128.5 million) along with the approximate estimate for the change in PM10 (29.3 μg/m^3) we attributed to the with/without comparison for the Clean Air Act Amendments in 2010. These estimates imply a marginal willingness to pay 10 times larger than the average we developed for the hedonic (\$356 per μg/m^3 versus \$34.60 per μg/m^3 in 2005 dollars). Clearly this estimate does not reflect the detailed components of the PE analysis any more than the use of the mean marginal willingness to pay adequately captures the diversity in hedonic property value estimates. What they do illustrate is the importance of an intermediate step in linking spatially delineated benefit measures to an economy wide CGE model. The answer for resolving this disparity is partially

[25] These estimates are reported in terms of PM2.5. We used a simple conversion PM2.5 = 0.55 x PM10 to approximate the implied change in PM10.

addressed by considering an index number question. That is, how should we aggregate spatially delineated air pollution measures?[26] One approach would use the logic of price and quantity index numbers and the Fisher factor reversal condition. Given an aggregate estimate of the benefits provided by a program can be developed using spatially delineated damage measures, then with a single, aggregate index of MWTP for that pollutant we can derive an index for the change in pollution (i.e. Δ pollution =damages/MWTP).

Columns (4) and (5) in Table 2 provide the parameters implied by each of these calibrations. In both cases, Q is set to the value implied by the value PM10 in 1950 (see Table 3) for the 1950 moments. For the 2005 moments μ is set to 93.5, the value implied by matching the PM10 and the value of G for 2005.[27] Q is determined by the feedback link with G as part of the calibration of the 2005 moments.

Table 4 provides a gauge for the model's fit using each of the two values for the air quality shares of income. In each case the model defines the moment to match the value share defined as the value of Q implied by the equilibrium G compared to a value for PM10 that was either 77.2% or 55.3% larger. Equally important, the feedback loop between G and Q was "shut off" for the three moments in 1950. As expected, the calibration does not yield perfect matches to the data. The largest discrepancies between data and model arise for the allocation to market services. As the size of the non-market share grows, the model does worse in matching the implied PM10 in 2005 and better in matching the monetary value share for changes in Q compared to income (defined in equation (7)).

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[26] See Smith [2012] for a discussion of the challenges in developing a time series for aggregate measures of air and water quality for the U.S.

[27] That is, we used the value of G implied by the data for calibrating the time allocation to G and the labor productivity implied for A_G. See Table 3.

The last two columns in Table 2 permit a comparison of how including air quality affects the calibrated parameters describing our amendment to Rogerson's model. Using our amended specification and the added moment with a relatively small value share for the Q moment changes the allocation parameter for goods versus the service composite and on the elasticity $\sigma_{GF} = 1/(1-\epsilon)$ between goods and the service composite. The share of goods is over five times what Rogerson's model implied and is insensitive (in relative terms) to the size of the value share associated to Q. The share of consumption remains relatively stable, as does the share parameters for services considering market purchased versus home production when the value share for Q is small.

The elasticity between goods and the composite of services is sensitive to the presence of non-separable Q and to the size of share attributed to these services. In interpreting these findings it is important to recognize that pollution is not spatially delineated, so the small share also implies a smaller marginal value (MRS) for Q. The calibration reconciles these moments with the time allocations and the pre-specified substitution between market and home production by forcing the elasticity between goods and composite services to be nearly zero. As the share for Q increases, and there is an increase in the marginal value of Q, then the parameter calibration changes. First, the share of services (markets versus home production) declines reflecting the fact that the composite of home production and air quality is more valuable at the margin to the household and the elasticity increases tenfold.

The subsistence parameter also switches from a negative value with low share for Q to a positive value for the larger share. The negative value for $\bar{G}$ implies, all else equal, a higher marginal value for an increment to the market good. There are offsetting changes in the values of other parameters that make a full assessment of the implications of this dimension of the calibration infeasible. The value for α_G drops by nearly twenty percent as the share for Q increases and the parameter determining the elasticity increases tenfold. Both would contribute to any judgment on marginal values for increments to market goods compared to the composite of market and augmented non-market services.

We can use Brown and Heien's derivation of the Slutsky terms for intra-group pairs of goods to suggest that the share selected for Q does *not* alter the substitution relationship between market goods and the composite of market and home produced services. A judgment about a positive or negative sign for the cross price effect of services on the demand for market goods is determined by the sign of $(1 - \sigma_{GF})$.[28] An increases in the value share for Q increases the σ_{GF} from .018 to .163 but it is never greater than one. As a result, goods and services remain substitutes for the representative household.

Another strategy for evaluating the effects of changes in the sets of parameters for different calibrations considers them within the original Rogerson's model. That is, we use the calibrated values for the parameters and "predict" the implied allocation of time between producing market goods, market services, and household production omitting Q. This task is repeated for each of the sets of parameter values associated with the two value shares attributed to Q. Table 5 provides these results.

The first columns provide the track record for the original Rogerson model. As expected, the Rogerson model exactly matches the allocation in 2003. Introducing air quality without recognizing its role in augmenting household services leads to under allocation of time to produced services compared to the 2003 allocations and over-allocations to goods and household produced services. The errors increase with the larger value share for Q, reflecting the larger

[28] Brown and Heien's equations are not numbered. The relationship for the Slutsky cross price effect is given on page 742. The Cobb Douglas top nest implies an overall elasticity of unity.

value for the elasticity between market goods and composite services. The time allocated to leisure declines somewhat, as is expected by the relative stability of α_C for the two value shares.

V. The Effects of Feedbacks

All the current CGE models in the U.S. and Europe leave out the feedbacks associated with air quality affecting household behavior. Recognizing these links in a general equilibrium model will necessarily imply that the final level of air quality is an endogenous outcome of the general equilibrium. Table 6 compares the calibrations of the amended Rogerson model with and without these feedbacks for each of the two value shares for Q. One difference in the calibration stands out in the no feedback case. The elasticity for household produced services and air quality varies by a factor of 100 as the Q-share changes. With feedbacks it is between 2.1 and 2.5, without it varies from 0.05 to 5.5 depending on the size of the Q-share used in calibration. The other parameters vary, generally in directions that are the opposite of the effects observed in the feedback specifications. That is, for the calibrations of the models with feedbacks, increases in the Q-share tend to reduce a parameter, the opposite effect is observed in the no feedbacks case. For example α_G and α_S decrease with increases in the Q-share with the feedback model and increase with no feedbacks. This change implies increasing the share of goods relative to leisure. The elasticity between market goods and the services composite moves in the same direction and remains smaller when the Q-share increases in the no feedback case.

We use the same strategy to evaluate the composite of parameter changes. Table 7 uses them to predict time allocations in the original Rogerson specification of the model. The errors are generally smaller for both of the values for the Q-share. This is not especially surprising because the parameters for the original Rogerson model do not include air quality and the "no feedback" calibration leaves out the link between market decisions and non-market responses.

Table 8 evaluates the no feedback model in relation to the data used to calibrate it. A comparison of these results with the earlier ones in Table 4 clearly favors the calibration incorporating feedbacks. The fit between the model and the data is worse in this no feedback case. This result is especially pronounced when the Q-share is larger. The poor predictions for H_N in 1950 and 2005 with the larger Q-share are especially notable. As expected from the definition of μ, the fit on the Q-share improves a bit as the Q-share increases but displays comparable performance to the feedback model. That is, the predicted share for Q has the largest error for calibrations using with the smallest share in setting the parameters and the error declines as the share increases.

What can be concluded from this comparison? First, soft linkages or no feedbacks *do influence* the characterization of the market economy. They *do not affect* our conclusions about substitution versus complementarity of market goods and composite services. When evaluated with the original Rogerson framework, one might easily conclude that the soft linkage has a "small edge" in terms of the errors in predicting time allocations.[29] However, when we consider how well the model as specified with non-separable Q fits the data, the conclusion would favor using the specification *with feedbacks*. Second, the size of the Q-share is very important to these conclusions. If we evaluate the fit based on matching Q-shares alone, then the calibration with Q-shares implying a larger MRS for Q favors the specification with feedbacks included.

VI. Gauging the General Equilibrium Effects of Large Rules

[29] This is generally comparable to the conclusion of Mayeres and Van Regemorter [2008] in assessing feedback effects in the GEM-E3 model. However, their specification assumed health expenditures were a perfect substitute for declines in air quality. Our approach allows for more general substitution that is endogenous to our calibration.

One of the reasons we proposed developing a simple model for GE analysis was to allow a transparent standard to gauge the plausibility of PE benefit cost analysis for new rules with economy-wide effects. This section illustrates how such a process might proceed using a stylized example. We strip away many important technical details of EPA's recent Clean Power Plan and use our model to consider whether the PE estimates for ancillary benefits attributed to the new rules would be judged as "plausible." Our analysis is an example. It should *not* be treated as a full scale assessment. In a serious assessment, both the structure of a simple general equilibrium model and the information from the regulatory impact analysis would need to be designed to match the key elements in the rule under study from the outset. Our goal is to demonstrate that *it could be done* and therefore could offer a separate basis for judging the plausibility of current PE practices with large new rules. This strategy is an alternative to developing large scale detailed models that seek to represent all aspects of the U.S. economy that might be impacted by different regulations. Instead our proposal is to consider small, nimble models can be designed and used for strategic assessments of whether a new rule is large enough to warrant, economy wide analysis due to its GE effects.

In August 2015, EPA released the final Regulatory Impact Analysis (see U.S. Environmental Protection Agency [2015b]) for the Clean Power Plan. The analysis assumes that the compliance period begins seven years after this final rule is issued (in 2022). By 2030, the analysis estimates that there would be about an 18.5 percent reduction in CO_2 emissions from the estimated emissions without the plan. A variety of options are provided to states. The EPA analysis estimates the best system of emission reductions (BSER) as performance rates for fossil fueled electric generating units as well as for natural gas combined cycle units. Based on each state's power plants in 2012, a separate goal was developed for each state measured as a mass (tons of CO_2 derived translating performance rates with each state's mix of allowed electric generating capacity to a total level of CO_2 emissions reduced) or a rate (a weighted average of emission performance rates in terms of pounds of CO_2 emission per net megawatt hours of electricity generated). Model rules are offered that allow for trading systems or technology based standards as part of the implementation process.

This array of information must be distilled to yield two specific adjustments to our model. We need the implied reduction in the ancillary pollution in a form that matches our model. This task means SO_2, NO_x and PM2.5 must be expressed as PM10 equivalents. In addition we need a simple estimate for the compliance cost of the rule. Our simplification dramatically reduces the complexity in the full details of the rule. With full information on the underlying details it would be possible to construct alternative aggregate indexes for the cost increase and for the spatially delineated change in air pollution. The final RIA documentation does not provide the intermediate detail that would be required for each of these tasks[30]. The absence of this detail is not crucial to our objectives because the goal is to demonstrate that a comparison *could* be undertaken. At the close of this section we return to the issue of whether this requirement to simplify undermines the logic for using simple GE models to judge more complex PE assessments.

When full compliance is reached, the RIA analysis estimates the analyzed cost increase to be 2.5 to 4 percent (see Tables 3.8 and 3.9 in U.S. Environmental Protection Agency [2015b]). Our focus is on the ancillary health benefits. The discussion in the RIA primarily considers reductions in SO_2 and NO_x. Reductions in particulate matter had to be computed outside the Integrated Planning Model used to estimate these other emission reductions. This difference is

[30] Of course, if the goal of a small scale assessment of GE effects was part of the design of the policy analysis for each RIA, then these data could be retained for constructing these indexes.

important for two reasons. First, most of the health benefits arise from particulate matter. The regulation's effects on PM2.5 are primarily indirect in that atmospheric concentrations of SO_2 and NO_x contribute to the formation PM2.5. The RIA develops these measures using Ben MAP-CE (Benefits Mapping and Analysis Program-Community Edition, see Abt Associates [2012]). The analysis used a benefit-per-ton emission reduction to develop the health benefits. This shorthand reduces the detailed atmospheric modeling underlying a full assessment to unit values per ton of emissions of PM2.5 or its precursors SO_2 and NO_x. While the specific analysis in the RIA was done on a disaggregate level, only the overall estimates for ancillary benefits are provided. There is no information on the implied values for the estimated reductions in PM2.5 concentrations due to reduced levels of SO_2 and NO_x in the atmosphere[31].

Two sets of computations underlie our measures for the reduction in PM10. When the annual benefits due to health effects in 2030 are converted to 2005 dollars, they range from 12.1 to 29.4 billion dollars. First, using a weighted average of the Fann, Fulcher and Hubbell [2009] measures for the values of a ton reduction in SO_2 and NO_x from electric generating units due to the effects of each pollutant on the implied reductions in PM2.5, we can recover an estimate for the "equivalent" reduction in PM10. That is, this reduction in PM10 would yield the same benefits as that associated with reductions in SO_2 and NO_x contributing to reduced particulate matter. Table 9 summarizes the elements for the inputs to our analysis of the Clean Power Plan (CPP). We selected the 4% cost increase and the middle estimate (2.15%) for the reduction in

[31] Our model is based on PM10 not PM2.5. An approximate link between PM2.5 and PM10 is used to adjust the results PM2.5 = .55 PM10. The distributions for PM10, measures of extreme values of PM10 and the distributions for PM2.5 change in different ways with each rule. This approximation does not adequately reflect these changes. It does reflect that any change in the modeling strategies used to gauge economy wide effects will impose new data needs. The current PE analysts for large rules develop this type of information for important sub-regions. When small GE models are used in these types of sensitive analyses it would be possible to identify the associated data needs at an early stage in the RIA development process.

PM10 to characterize the effects of the plan as if full compliance occurred in a single year–our last year 2005.

Our preferred calibration of the extended Rogerson model (i.e. the one with Q-share of .0536) is used for the analysis of the GE effects. This calibration was selected because the lower Q-share is consistent with the empirical literature that has attempted to measure air quality benefits relative to income. The first of these studies by Sieg et al. [2004] found annual benefits for air pollution reduction ranging from 6 to 21 percent that were 1 to 2 percent of household income. Our low Q-share is for a larger improvement, more than 3.5 times the upper end of this range. Assuming proportionate increases in the incremental value attributed to reduced air pollution (approximately constant marginal willingness to pay) these estimates would imply values for a Q-share comparable to our estimate. Tra's [2010] more recent analysis with a different specification for a sorting model also applied to Southern California, considered larger changes in ozone—25 to nearly 40%. He found annual benefits in the range of 2 to 3 percent of income. Using the same scaling we would select the low Q-share. Finally, Freeman's [1982] classic analysis of the benefits of air quality improvements arrived at best estimates for air pollution related benefits associated with a 20% reduction in the major criteria pollutants amounted to about 1.1 percent of national income in 1978. Applying the same simple extrapolation to his results we would have estimates for a Q-share about 4.2 percent. Thus, the literature and the relative magnitude of the estimated benefits due to the effects of the Clean Power Plan on the criteria pollutants would suggest selecting a model that assigns a more modest role to air pollution.

Our strategy requires that the model is first solved for baseline conditions that define Q_0. With this baseline, the change to productivity parameter for G (reflecting the cost increase) as well as the change to μ representing how regulations impact the "system" defining Q are introduced into the model. The GE solution implies a new value of Q which need not correspond to the 2.15% reduction in PM10 we attributed to the plan. Taken together, the Q and Q_0 and the MRS evaluated at the new equilibrium allow computation of an implied Q-share for the policy - MRS times $(Q - Q_0)$ relative to wage compensation. Comparing this implied value for this ratio to the share using the PE benefit measure provides our gauge of the effects of GE responses for PE benefit estimates. Table 10 summarizes the results from this process.

The last row of the Table 10 compares the PE and GE benefit measures. We do not include costs in the PE estimates used for the comparison in Table 10. The PE benefit measures are compared in 2005 dollars. The range corresponds to the range in the RIA for the high and low values of ancillary benefits as documented in Table 9. This comparison implies that the low PE benefit measure is less than what our model would imply for GE net benefits of the plan and the high end of the range for the PE benefits is too large—about twice what our model implies for the GE case. Several qualifications to these results are important. Our model includes the beneficial effects associated with reductions in conventional air pollutants and the estimated compliance costs. Thus the costs affect the ultimate GE allocations of time to market goods, market services and home production. Substitution effects in response to relative prices changes as well as the effect of the air quality change on home produced services imply we do not realize the technically prescribed reduction in PM10. In effect, augmented home services alter the service/goods mix enough that realized emissions reduction does not match the change implied by the change in μ.

The potential importance of the selected Q share for the model's results does not, in our view, reduce the potential for using simpler GE models to gauge the importance of economy wide effects. Instead it identifies a need for change in the way we construct benefit measures. We do not have accumulated experience to use in interpreting what the Q-share should be. Our earlier discussion explaining why we favored the smaller share assembled a "patchwork" of recent research together with an early assessment of the benefits from reducing all air pollutants to develop some intuition. The importance of the Q-share to judgments about what are small or large interventions with GE effects suggests a need to reorient research in non-market valuation so it is possible to measure benefits from environmental improvements in a way that gauges their magnitude in relation to household income or consumption expenditures.

VII. Implications

Shortly after the inauguration in President Obama's first term, the Tobin Project released a volume entitled New Perspectives on Regulation. Greenstone's chapter in this volume called for reform in regulatory design and evaluation. Measuring benefits or costs for regulations, in his view, requires as much controlled testing as is feasible.[32] His system would involve a restructuring of statutes governing regulations so they can be evaluated. This is a tall order. In the meantime we need strategies to allow the assessment of the benefit measures to "discipline the discretion" in ex ante policy evaluation.

Current policy analysts charged with evaluating large scale environmental policies have recognized the importance of taking account of economy-wide effects in the development of benefit cost analyses. However, they have opted for using models that recognize the complex interactions of environmental contaminants in the atmosphere and then using *soft links* of the results from these models to equally large and complex economic models of market transactions.

[32] See Greenstone [2009] p. 112.as well as his concluding discussion with specific proposals (pp123-124)

As a result, we cannot evaluate the importance of the interactions of nature and the economy for the relevance of the information in these benefit cost assessments.

We have demonstrated that this can lead to important misrepresentations of a simple economy, and we suggest as an alternative that these assessments take a page from modern macro-economic analyses of policy. Frame simple but *strategic* models that focus on the issue relevant to the policy assessment. Acknowledge they are not comprehensive but are instead designed to gauge the plausibility of policy analyses. Our example outlined how this task could be undertaken for environmental policy, with a stylized example of the Clean Power Plan. This approach is consistent with the logic advocated by Harberger [1964] in the context of excess burden[33]. General equilibrium or economy wide effects spread across markets based on the cross price or substitution effects that reflect non-separabilities in preferences.[34]

Our discussion and examples here have focused on air pollution policy but the same issues can arise with water pollution policies. In this case regulations also affect spatially delineated facilities and their aggregate effects must be "added up" in some way to account for the economy wide implications. As was the case with air quality modeling, analysis of the effects of these policies on water quality must be spatially delineated to take account of the features of emissions in different watersheds. Economy wide assessments require that we recognize the need to aggregate both the compliance costs imposed on key sectors *and* the realized impacts on environmental quality. Models need to reflect *both* the cost and the benefit effects of rules. Non-separability in preferences is central to the strategies used to measure the tradeoffs people would make to improve environmental quality. It should also be an integral part in any description of

[33] See Goulder and Williams for a modern update and extension to Harberger's analysis
[34] Non-separability in production functions would also arise in a more general model.

how consumers would respond to the price and environmental quality effects of large scale changes in environmental policy.

Table 1: Allocation of Labor Hours in U.S.[a]

	Market Goods (H_G)	Market Services (H_S)	Home Production (H_N)
1950	.115	.135	.250
2003	.058	.194	.213
2005	.070	.232	.204

[a] Total hours are normalized to sum to unity. The figures for 1950 and 2003 are from Rogerson [2008] Table 1 and for 2005 from Duernecker and Herrendorf [2015] Table 7, with the allocation of market work between goods and services determined to correspond to the same proportions as Rogerson.

Table 2: Calibration of Base Rogerson Model and Extension with Air Pollution

Parameters	Rogerson (2008)	Our Replication	2005 & γ_N	Feedback (1)	Feedback (2)
Share of goods (α_G)	0.07	0.07	0.1	0.498	0.414
(market vs. services)					
Share of services (α_S)	0.46	0.46	0.47	0.403	0.267
(markets vs. home production)					
Share of consumption (α_C)	0.5	0.5	0.5	0.556	0.586
Share of home (α_N)	—	—	—	0.619	0.338
home vs. nature					
Elasticity of substitution market goods vs. services	0.44	0.48	0.5	0.018	0.163
$\sigma_{GF} = 1/(1-\epsilon)$					
Elasticity of substitution - home production	1.82	1.82	1.82	1.82	1.82
$\sigma_{SN} = 1/(1-\eta)$					
Elasticity for effect of air quality	—	—	—	2.47	2.11
$\sigma_{NQ} = 1/(1-\varphi)$					
Subsistence market goods $\bar{G}$	0.035	0.039	0.032	-0.024	0.015
Productivity					
Goods (γ_G)	2.48	2.48	2.48	2.48	2.48
Services (γ_S)	1.44	1.44	1.44	1.44	1.44
Household (γ_N)	-0.20	-0.216	0.07	0.07	0.07
Q-share	—	—	—	0.0536	0.1747

Table 3: Values and Sources for the Construction of Q Share Measures for Calibration

	Variable	Value	Year	Source
A. Analysis for Low Q-share	PM10	110.5 μg/m³	1950	Matus et al. [2008]. Source -- David Mintz in personal communication in 2003. Derived from average of second max of PM10. Applies 0.415 to average of second maximum. See U.S. EPA [1996]
	PM10	25.2 μg/m³	2005	
	Proportionate Change	0.772		
	MRS	$34.60	2005	Average from Smith and Huang [1995] adjusted to convert to PM10
	μ	93.5	2005	Ambient concentration of PM10 in 2005 divided by value of G, which is product productivity parameter A_G and H_G (=.2693).
	Share of Aggregate Wage Compensation	0.0536		Wage compensation comes from the Labor Compensation (Compensation of Employees) series from the Groningen Growth and Development Centre Databases. We used the EU KLEMS Database, accessed through http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect
B. Analysis for High Q-share	PM10	23.64 μg/m³	With Clean Air Act	U.S. Environmental Protection Agency [2011] Box 4-1. Population weighted average of PM2.5 for New York, Pittsburgh, Chicago, Los Angeles, scaled by (1/0.55)
	PM10	52.94 μg/m³	Without Clean Air Act	U.S. Environmental Protection Agency [2011] Box 4-1. Population weighted average of PM2.5 for New York, Pittsburgh, Chicago, Los Angeles, scaled by (1/0.55)
	Proportionate Change	0.553		
	Aggregate Benefits	$1.3 trillion	2006 dollars for 2010	U.S. Environmental Protection Agency [2011] Table 7.5
	Share of Aggregate Wage Compensation	0.175		Wage compensation comes from the Labor Compensation (Compensation of Employees) series from the Groningen Growth and Development Centre Databases. We used the EU KLEMS Database, accessed through http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect

Table 4: Comparison of Data and Model Estimates with Low and High Q-Shares

	Q value share = .0536		Q value share = .1747	
	Data	Model	Data	Model
1950				
H_G	0.1150	0.1149	0.1150	0.1154
H_S	0.1350	0.1629	0.1350	0.1670
H_N	0.2500	0.2314	0.2500	0.2526
2005				
H_G	0.0700	0.0597	0.0700	0.0610
H_S	0.2320	0.2103	0.2320	0.2040
H_N	0.2040	0.2081	0.2040	0.2061
PM10	25.2000	24.4926	25.2000	21.9428
Q value share	.0536	.1073	.1747	.1695

Table 5: Performance of Model with Feedbacks in Original Rogerson Specification [a]

	Rogerson -2003		Q share = .0536	Q share = .1747
	Data	Model		
H_S	.1940	.1940	.1642	.0748
			(0.85)	(0.39)
H_G	.0580	.0580	.0732	.0988
			(1.26)	(1.70)
H_N	.2130	.2130	.2780	.3900
			(1.30)	(1.83)

[a] The numbers in parentheses below the third and fourth columns are the ratio of predicted allocation of time to market services, market goods, and home production for the models with air quality relative to the corresponding value from the Rogerson model.

Table 6: Calibration With and Without Feedbacks for Low and High Q-Shares

Parameters	Feedback		No Feedback	
	(1)	(2)	(3)	(4)
Share of goods (α_G)	0.498	0.414	0.411	0.455
(market vs. services)				
Share of services (α_S)	0.403	0.267	0.491	0.523
(markets vs. home production)				
Share of consumption (α_C)	0.556	0.586	0.578	0.389
Share of home (α_N)	0.619	0.338	0.998	0.502
home vs. nature				
Elasticity of substitution market goods vs. services	0.018	0.163	0.019	0.098
$\sigma_{GF} = 1/(1-\epsilon)$				
Elasticity of substitution - home production	1.82	1.82	1.82	1.82
$\sigma_{SN} = 1/(1-\eta)$				
Elasticity for effect of air quality	2.47	2.11	5.55	0.046
$\sigma_{NQ} = 1/(1-\varphi)$				
Subsistence market goods $\bar{G}$	-0.024	0.015	-0.081	0.026
Productivity				
Goods (γ_G)	2.48	2.48	2.48	2.48
Services (γ_S)	1.44	1.44	1.44	1.44
Household (γ_N)	0.07	0.07	0.07	0.07
Q-share	0.0536	0.1747	0.0536	0.1747

Table 7: Performance of the Model Without Feedback in Original Rogerson Specification[a]

	Rogerson Model	No Feedback	
		Q share = .0536	Q share = .1747
H_S	.1940	.2394	.1609
		(1.23)	(0.87)
H_G	.0580	.0679	.0712
		(1.17)	(1.23)
H_N	.2130	.2122	.1135
		(0.99)	(0.53)

[a] The numbers in parentheses below the values in the second and third columns are the ratio of the predicted allocation of time to market services (H_S), market goods (H_G), and home production (H_N) for the models calibrated with air quality moments without feedbacks relative to the corresponding values predicted from the original Rogerson model.

Table 8: Comparison of the “No Feedback” Model’s Fit with Low and High Q-Shares

	Q value share = .0536		Q value share = .1747	
	Data	Model	Data	Model
1950				
H_G	.1150	.1163	.1150	.1141
H_S	.1350	.1591	.1350	.2148
H_N	.2500	.2734	.2500	.0098
2005				
H_G	.0700	.0723	.0700	.0708
H_S	.2320	.2142	.2320	.1414
H_N	.2040	.2165	.2040	.1277
PM10	25.2000	25.2210	25.2000	25.2210
Q value share	.0536	.0001	.1747	.1319

Table 9: Selected Components of EPA RIA's Analysis of Clean Power Plan

Measure and Source	Estimate
Cost Estimates (2011 dollars, billions)	
Baseline Costs (Table 3.9, U.S. EPA [2015])	$ 201.3
Annualize Compliance Costs	
Rate Based	$ 8.4
Mass Based	$ 5.1
Ancillary Health Benefits (2011 dollars, billions, Table 4.3i, U.S. EPA [2015])	
Rate Based (3% discount rate)	$ 14 to $ 34
Mass Based (3% discount rate)	$ 12 to $ 28
Benefit per Ton Precursor SO_2 and No_x (Fann et al. [2009], Figure 4)	
Electric Generating Units (3% discount rate)	
EGU SO_2 (2006 dollars)	$ 82,000
EGU No_x (2006 dollars)	$ 15,000
Weighted Average [a]	$ 50,510
Estimate for Equivalent Reduction in PM10 (percent)	
Rate Based	2.15 to 5.22
Mass Based	1.84 to 4.30

[a] The per ton estimates are weighted by estimated reductions in SO_2 and No_x for the rate based plan in 2030. See Table ES.2 in EPA [2015].

Table 10: Estimated GE Bounds for EPA's PE Benefits for Clean Power Plan

	Calibrated Model
	Q-share = .0536
Cost Increase (%)	4.0
Change in PM10 Emission (%)	-2.2
Computed Change in GE PM10 (%)	-1.55
GE Q-share of Clean Power Plan	.0021
Ratio of PE Benefits to Benefits for Estimated GE	0.82 to 1.99

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Appendix A.

(1) $U(C, 1-H) = \alpha_c \text{In}(C) + (1-\alpha_c)\text{In}(1-H)$

C = composite consumption

$1-H$ = leisure

(2) $C = (\alpha_G (G-\bar{G})^{\epsilon} + (1-\alpha_G)F(S,N)^{\epsilon})^{\frac{1}{\epsilon}}$

G = market goods

S = market services

N = non-market services or home production

$$\sigma_{GF} = \frac{1}{1-\epsilon}$$

(3) $\text{F}(S,N) = (\alpha_S S^{\eta} + (1-\alpha_S)N^{\eta})^{\frac{1}{\eta}}$

$$\sigma_{SN} = \frac{1}{1-\eta}$$

(4) $E = \theta \cdot G$ *(emissions)*

$AB = \pi \cdot E$ (*ambient concentration*)

$Q = \frac{1}{AB} = \frac{1}{\theta \cdot \pi \cdot G}$ (*implicit quality*)

$= \frac{1}{\mu \cdot G}$ where $\mu = \theta \cdot \pi$

Budget Constraint

$$P_G \cdot G + P_S \cdot S = (1-\tau)(H_G + H_S) + T$$

τ = income tax rate

T = transfer of taxes to household

($T = \tau \cdot (H_G + H_S)$, the link between choices of the connection between the compensation for work time and this transfer is not recognized by consumer)

Time Constraint

$$H_G + H_S + H_N + H_L = 1$$

$$H = H_G + H_S + H_N$$

So $1 - H = H_L$ (leisure)

Allow for labor productivity

(5) Household Services vs. Market Services

$$\frac{\alpha_S}{1-\alpha_S}\left(\frac{S}{N}\right)^{\eta-1} = \frac{A_N}{(1-\tau)A_S}$$

(6) Goods vs. Services

$$\left(\frac{1-\alpha_G}{\alpha_G}\right)\cdot\left(\frac{\alpha_S F^{\epsilon-\eta} S^{\eta-1}}{(G-\bar{G})^{\epsilon-1}}\right) = \frac{A_G}{A_S}$$

(7) Hours Worked in the Goods Sector vs. Leisure

$$\frac{\alpha_C \alpha_G (1-\tau) A_G (G-\bar{G})^{\epsilon-1}}{C^{\epsilon}} = \frac{1-\alpha_C}{1-H}$$

(3') $F(S, N) = \left[\alpha_S S^\eta + (1-\alpha_S)\,(\alpha_N N^\varphi + (1-\alpha_N) Q^\varphi)^{\frac{\eta}{\varphi}}\right]^{\frac{1}{\eta}}$

Q = measure of amenity services

$\sigma_{NQ} = \frac{1}{1-\varphi}$

Appendix B: Logic for Analysis Structure

Resource limitations, both financial and time, prevent EPA from conducting full benefit cost analyses for proposed rules. As a rule, the typical benefit analysis selects what are described as "analytical snapshot years" (see U.S. Environmental Protection Agency [2015]). These selections are intended to describe a year when the rule being evaluated is fully implemented (or close to it). When they are in a future year other economic variables are projected based on established economic forecasts. The benefit measures are presented in real terms, usually selecting a year close to the year the report is issued. Unit benefit measures such as the VSL are adjusted for income effects with assumed income elasticities based on the literature.

Our analysis follows this basic logic by selecting a candidate year but instead uses a year (in our case 2005) when consistent measures for the variables Rogerson used in the macro model are available. This strategy implies our focus is on three features of the environmental variables contributing to our added moment: the proportionate change in the PM10 (and associated change in Q) implied by the right side of the moment (given in equation 7); the measure of the economic value for this change relative to wage compensation for a year as close to the year of the benefit measure; and measures for the value of PM10 for the years when the feedback effect was not imposed.

The specific form of the moment for $(Q - Q_0)$ adjusted Q_0 so that we reproduced the proportionate change implied by $(PM10_0 – PM10)/ PM10_0$.