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Exploring the General Equilibrium Costs of Sector-Specific Environmental Regulations[1]

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Abstract

The requisite scope of analysis to adequately estimate the social cost of environmental regulations has been subject to much discussion. The literature has demonstrated that engineering or partial equilibrium cost estimates likely underestimate the social cost of large-scale environmental regulations and environmental taxes. However, the conditions under which general equilibrium (GE) analysis adds value to welfare analysis for single-sector technology or performance standards, the predominant policy intervention in practice, remains an open question. Using a numerical computable general equilibrium (CGE) model, we investigate the GE effects of regulations across different sectors, abatement technologies, and regulatory designs. Our results show that even for small regulations the GE effects are significant, and that engineering estimates of compliance costs can substantially underestimate the social cost of single-sector environmental regulations. We find the downward bias from using engineering costs to approximate social costs depends on the input composition of abatement technologies and the regulated sector.

Keywords: environmental regulation, general equilibrium, social costs

JEL Classification: D58, Q52, Q58,

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[1] The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency (EPA).

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1 Introduction

The social cost of a regulation is the total burden that the action will impose on society and is defined as the sum of all opportunity costs incurred because of the regulation. An opportunity cost is the lost value of all goods and services that will not be produced and consumed as resources are moved away from production and consumption activities towards pollution abatement. To be complete, an estimate of social cost should include both the opportunity cost of current consumption that will be foregone due to regulation, and the loss that may result if the regulation reduces capital investment and thus future consumption. While the definition of social cost is firmly established and is well articulated in many textbooks on applied welfare analysis, the scope of analysis required to estimate the social cost of regulations in practice remains an open question.

In theory, in the absence of market distortions and under competitive price adjustments in all markets, the social cost of a regulation can be assessed with a partial equilibrium (PE) model of the directly regulated market (Just et al., 2004; Harberger 1964).[4] This is because while a policy may have general equilibrium effects, market clearing conditions effectively "cancel" out these effects in other markets (Farrow and Rose 2018). In addition, research has found that PE cost estimates may differ significantly from general equilibrium (GE) costs due to interactions with pre-existing tax distortions (e.g., Bovenberg and deMooij, 1994; Bovenberg and Goulder, 1996; Goulder, et al., 1997; Goulder, et al., 1999; Lithgart and van der Ploeg, 1999; Fullerton and Metcalf, 2001; Pizer et al., 2006), and that this may hold for relatively small single-sector policies depending on the policy instrument (Goulder, et al., 1999).

The U.S. EPA recently convened a Science Advisory Board (SAB) panel of experts to consider, among other questions, the conditions under which GE analyses of prospective regulations add value on top of the engineering or PE analyses typically conducted.[5] The SAB panel's advice was that a GE analysis is most likely to add value when the cross-price effects *and* pre-existing distortions (e.g., taxes, market power, other regulations) are significant. An open question remains as to what constitutes a significant cross-price or distortionary effect or, as stated by Hahn and Hird (1990), when it is reasonable to assume away these potentially "second-order effects."

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[4] When impacts outside of the regulated market are not expected to be significant, the social cost of the regulation can be approximated by the sum of compliance costs and the opportunity cost of the reduction in output in the directly affected market, assuming few transition costs.

[5] See https://yosemite.epa.gov/sab/SABPRODUCT.NSF/0/07E67CF77B54734285257BB0004F87ED

In this paper, we use a detailed computable general equilibrium (CGE) model to compare the difference between the social cost of environmental regulations and ex ante engineering estimates of compliance costs and explore the conditions under which GE analysis may add value in practice. We vary a wide range of characteristics that may affect the social cost of regulation including the sector being regulated, the magnitude of the regulation, whether regulatory requirements are differentiated by plant vintage, and the type of inputs required for compliance. We find that even for small regulations both the output substitution and tax interaction effects are significant, and ex ante compliance cost estimates tend to substantially underestimate the social cost of regulation independent of the sector subject to regulation or the composition of inputs required for compliance.[6] This result is robust across a large number of regulatory scenarios and a series of sensitivity analyses over parametric and structural assumptions.

We find that the details of the regulation under consideration are important for determining the difference between estimates of the social cost and ex ante compliance costs. Therefore, it would be difficult to generalize our results to develop an ad hoc adjustment to ex ante compliance costs to account for missing costs. However, our results do provide practical information that can be used to assess when GE analyses tailored to a specific rulemaking might add the most value. First, when the net benefits based on engineering costs are relatively close to zero, particularly if compliance is capital or labor intensive, it may be important to conduct a CGE analysis to determine whether the GE effects substantively affect the magnitude and possibly the sign of the net benefits. Second, if multiple regulatory options are being considered and they differ significantly in their input composition, GE analysis can highlight potentially significant differences in their social costs by netting out transfers embedded in producer prices that can differ across inputs and would be implicitly included in engineering or partial equilibrium analyses. Third, since the ratio of the social to engineering costs is not very sensitive to the size of a regulation, even small regulations may be associated with important GE effects. Fourth, a regulation's interaction with pre-existing taxes on capital will be greater for sectors whose output is, either directly or indirectly, important for the formation of physical capital.

The remainder of the paper is organized as follows. In Section 2 we provide background on why and how the social costs of regulation are expected to differ from ex ante compliance cost estimates in theory and in practice. In Section 3 we describe the CGE model used for our analysis and the regulatory scenarios we

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[6] A caveat for our analysis is that we do not consider abatement cost heterogeneity across firms and the potential for intra-sectoral domestic production substitution when comparing estimates of social costs and compliance costs.

consider. In Section 4 we present our results and in Section 5 we discuss the implications of our findings and important caveats.

2 Background

Pizer and Kopp (2005) characterize the choice of the method for estimating costs as related to the types of costs anticipated from the policy – direct compliance costs, foregone opportunities, lost flexibility, etc. – as well as the degree to which the policy will "meaningfully influence" the prices of goods and services. When the effects of a regulation are expected to be confined to a single market, with initial domestic production level Q and a homogeneous compliance cost of C per unit of output, the ex ante compliance cost is $Q \times C.$ In many instances, compliance costs may place upward pressure on the output price in the regulated sector leading to an output substitution effect (i.e., the sector contracts), which imposes an additional cost in the form of lost surplus associated with the output no longer produced or consumed. The compliance costs of an environmental regulation may also differ from the social costs in the presence of GE feedbacks. Yohe (1979) demonstrated that even in a highly simplified GE framework, environmental regulations that target a single sector will impact the output price of other sectors via factor markets. Changes in relative factor and commodity prices due to environmental regulation suggest that both the compliance costs and the lost surplus from the output substitution effect are a function of these GE effects.

Early work on the GE effects of environmental regulation assumed a static, first-best setting where the stock of primary factors was fixed and a single pollutant was the only distortion in the economy. For instance, using a highly aggregated CGE model with production as a function of primary factors (capital, labor, and land) and intermediate inputs, Kokoski and Smith (1987) found that PE welfare estimates of environmental policies that directly target emissions in a single sector could be relatively close approximations to the GE social costs, but that the PE welfare estimates were a poor approximation for broader policies that target emissions in multiple sectors. Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) developed econometrically-estimated, dynamic CGE models of the U.S. economy that explicitly account for the role of taxes to assess the social costs and impact on economic growth, respectively, of U.S. environmental regulations. Both studies find that the dynamic nature of the economy is important for understanding the economic effects of environmental regulation, and Hazilla and Kopp (1990) conclude that inter-temporal feedbacks are important for understanding how social cost differs from compliance cost estimates. When the assumption of a fixed capital stock is relaxed and is instead endogenously determined, the contraction in the economy from environmental regulation leads to a reduction in investment and a transition to a lower steady state level of capital. This effect is not captured in an engineering or PE analysis.[7]

Early work on the impact that pre-existing distortions have on social cost estimates focused on the interaction between environmental regulations and pre-existing labor taxes. By increasing the price of consumption relative to leisure, environmental regulations can exacerbate the inefficiencies of labor market taxes leading to negative welfare effects (Goulder, et al., 1997). Large pre-existing taxes on labor already discourage individuals from working as much as they would otherwise. If an environmental regulation lowers real wages it may lead individuals to work even fewer hours and increase the deadweight loss associated with the labor tax. Given that pre-existing distortions in the labor market are large, even a small change in labor supply induced by a new policy can have a large tax interaction effect that would not captured by cost estimates focused on directly affected sector (Goulder and Williams, 2003). Using analytical GE models, a number of researchers demonstrated that the tax-interaction effect causes the optimal pollution tax to be lower than the Pigouvian tax, even when revenues are used to reduce the distortionary labor tax (e.g., Bovenberg and de Mooij, 1994; Bovenberg and van der Ploeg, 1994; Parry, 1995, Parry, 1997; Ligthart and van der Ploeg, 1999). In other words, pre-existing distortions raise the marginal social cost of pollution abatement relative to the first-best setting.[8]

There is theoretical and numerical evidence that GE effects may be of first-order importance for estimating the social cost of certain environmental regulations. However, interactions between regulatory compliance costs and tax distortions may be sensitive to key assumptions. For instance, the shape of the marginal cost curve in the regulated sector has implications for the GE effects through its effect on the

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[7] For instance, Hazilla and Kopp (1990) examined the impact of the Clean Air and Clean Water Acts, on the U.S. economy and estimated that sectors which bore no direct compliance costs experienced output reductions of almost 5% in 1990. Similarly, the U.S. Environmental Protection Agency (EPA) found that the Clean Air Act Amendments may notably impact output in sectors with little to no direct regulation (US EPA, 2011).

[8] An initial focus of this literature was on the ability of environmental policy to generate revenue to reduce distortionary taxes and partially offset the tax-interaction effect. The hypothesis is that non-revenue raising policies, which represent nearly all environmental regulations in practice, will have higher social costs than revenue-raising policies due to an inability to offset the tax-interaction effect. As Fullerton and Metcalf (2001) noted, the issue is not the lack of government revenue but scarcity rents that are not capture by the government. Therefore, technology and performance standards that do not generate large scarcity rents, may have a tax-interaction effect of similar magnitude to a revenue-neutral emissions tax (numerically demonstrated by Goulder, et al. (1999). An exception is the case where input substitution is a cost-effective compliance option, in which case a technology standard will lead to a larger output price effect and in turn a larger tax interaction effect than a performance standard.

incidence of the compliance costs and therefore, the disincentive provided to labor. In the short- to medium-run, when rigidities in the production process lead to an upward sloping marginal cost curve, a portion of the compliance costs will be distributed to owners of capital through lower rental rates, thereby potentially lowering the labor tax-interaction effect relative to the case of constant returns to scale production (Murray et al, 2005). The degree of substitutability between the regulated sector's commodity and leisure can also affect the size of the tax interaction effect, especially for sectors where a large share of output is used for final consumption (Parry, 1995). The lower the degree of substitutability between the commodity and leisure, the smaller the tax interaction effect and in turn the social cost. For sectors whose production is primarily used as an intermediate input to production, the ease with which other sectors can substitute away from its use may be an important characteristic.[9] The difference between the GE estimates of social cost and engineering or PE estimates of compliance costs also is conditional on the characteristics of the regulated sector. For example, the composition of inputs to production in the regulated sector relative to the rest of economy and the substitutability across those inputs will affect the relative price changes induced by the policy intervention (Yohe, 1979). Given the importance of these assumptions, Murray, et al. (2005) conclude that generalizations about the difference between compliance costs and social costs should be approached with caution.

Regulatory design may also affect the difference between the GE social cost and engineering-based compliance cost estimates. For example, vintage differentiated regulations (e.g., new source performance standards) that erect a barrier to entry can generate rents for owners of existing capital through larger decreases in the net real wage and a large tax-interaction effect relative to a regulation affecting all sources (Fullerton and Metcalf, 2001). The composition of inputs required to abate pollution may also influence the GE effects if there is a bias towards inputs from distorted markets such as those for capital and labor. We discuss how the way a regulation is represented in a CGE model may influence social cost estimation in Section 3.2.

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[9] A related CGE-based literature finds that environmental policies in already distorted sectors or that result in larger changes in distorted factor markets are less cost effective than policies that target less distorting sectors or cause smaller changes in distorted factor markets. For instance, Pizer, et al. (2006) found that excluding highly distorted sectors from an economy-wide cap-and-trade made no difference or even slightly lowered the cost of the policy, while Goulder, et al. (2016) demonstrated that the advantages of a price-based approach over an emissions standard are less clear once its distortionary effects on capital and labor markets are considered.

3 Methods

The most common approach to estimating the social cost of a regulation in a general equilibrium setting is a computable general equilibrium (CGE) model. CGE models assume that for some discrete period of time an economy can be characterized by a set of conditions in which supply equals demand in all markets. When a government policy, such as a tax or a regulation, alters conditions in one market, a general equilibrium model determines a new set of relative prices for all markets that return the economy to equilibrium. These relative prices determine changes in sector outputs, demand for factors of production, intra-national and international trade, investment, and household consumption of goods, services, and leisure (U.S. EPA, 2010). The social cost of a specific regulation is estimated as the amount of money households would be willing to pay in the baseline to avoid the regulation and the burdens it imposes absent of the benefits of the regulation. Section 3.1 describes the CGE model we use to examine the social cost of regulation. Section 3.2 discusses the approaches we take to introduce specific types of environmental regulation into the model and estimate their social costs.

3.1 Model

SAGE is an inter-temporal CGE model of the U.S. economy covering the period 2016 through 2061 and is resolved at a subnational level.[10] The model is similar to the class of calibrated CGE models regularly used to analyze environmental and energy policies (e.g., Caron and Rausch, 2013; Chateau et al., 2014; Ross, 2014). In this section, we provide a general description of the model. See Marten and Garbaccio (2018) for detailed technical documentation of the model.

The model represents the nine Census regions of the United States (Figure 1). Trade follows an Armington specification, where goods are differentiated by their origin (Armington, 1969). For a given region, the model assumes differentiation between local goods, intra-national imports, and international imports. Substitution possibilities across these sources are defined by a nested constant elasticity of substitution (CES) function (Figure 2).

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[10] We use a recursive naming convention: **S**AGE is an **A**pplied **G**eneral **E**quilibrium model.

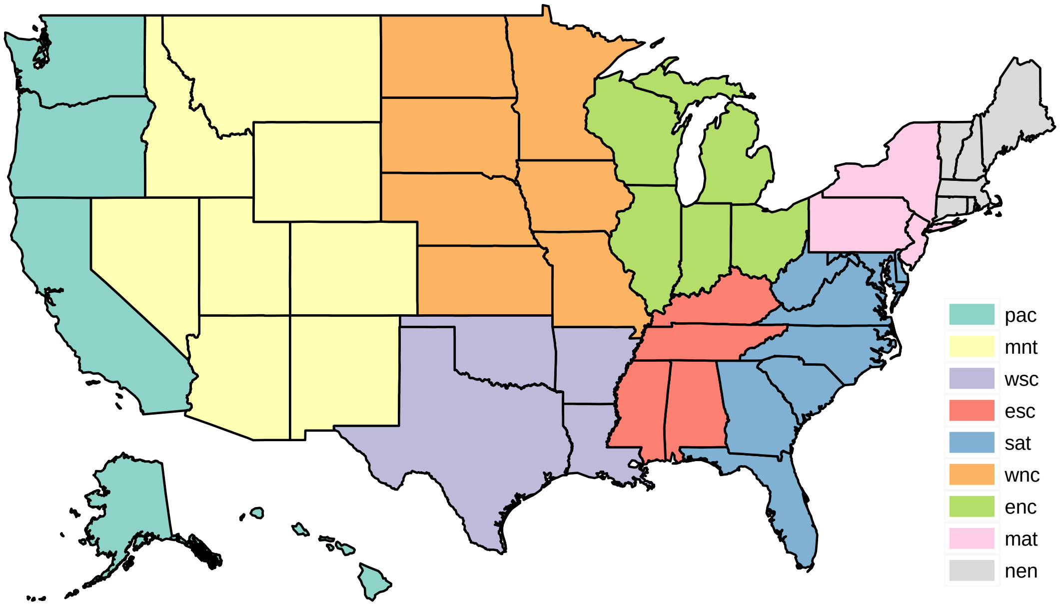

Figure 1: SAGE Regions

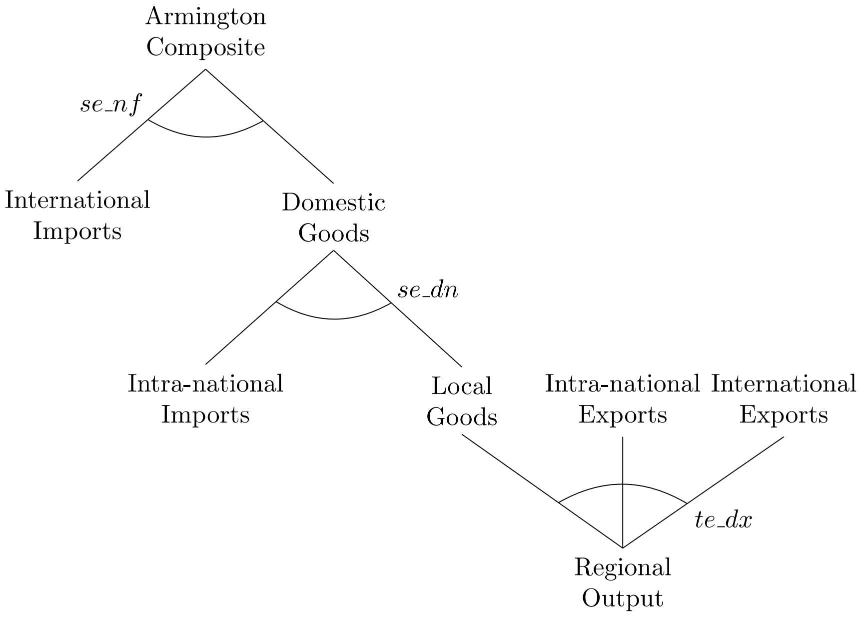

Figure 2: Armington Trade Specification

The first decision in each Armington composite is between consuming locally produced goods and those imported from other regions within the United States. Intra-national imports are assumed to be homogeneous with a single national market-clearing price. Next, the local and national bundle is combined with international imports to form an aggregate Armington composite good. Similarly, regional output can be consumed locally, exported intra-nationally, or exported internationally. The ability to move regional output between markets is controlled by a constant elasticity of transformation (CET) function (Figure 2). While the price of foreign exchange is endogenously determined, international demand and supply are assumed to be perfectly elastic following the small open economy assumption.

Within each region, production is disaggregated into 23 sectors, with a focus on manufacturing and energy as these sectors are the typical purview of environmental regulation at the federal level (Table 1). In most sectors, production is assumed to be constant returns to scale where the production function is defined by a nested CES function (Figure 3). Firms make decisions about the relative use of primary factors (i.e., capital and labor) and energy, and then the relative use of other intermediate material inputs compared to the energy and value-added composite. The energy good is a composite of primary energy sources (i.e., coal, natural gas, and refined petroleum products) and electricity. It is assumed that firms initially determine the relative use of primary energy sources followed by the relative use of primary fuels compared to electricity. The sub-nest combining non-energy intermediate inputs is assumed to be Leontief.

Table 1: SAGE Sectors

Manufacturing		Energy	
bom	Balance of manufacturing	col	Coal mining
cem	Cement, concrete, & lime manufacturing	cru	Crude oil extraction
chm	Chemical manufacturing	ele	Electric power
con	Construction	gas	Natural gas extraction & distribution
cpu	Electronics and technology	ref	Petroleum refineries
fbm	Food & beverage manufacturing		
fmm	Fabricated metal product manufacturing	Other	
pmm	Primary metal manufacturing	agf	Agriculture, forestry, fishing & hunting
prm	Plastics & rubber products	hlt	Healthcare services
tem	Transportation equipment	min	Metal ore & nonmetallic mineral mining
wpm	Wood & paper product manufacturing	srv	Services
		trn	Non-truck transportation
		ttn	Truck transportation
		wsu	Water, sewage, & other utilities

Sectors associated with fixed factor inputs, such as land or natural resources, have a production structure that deviates from the one presented in Figure 3. The presence of a fixed factor suggests that the production function in those sectors should exhibit decreasing returns to scale to more accurately represent the responsiveness of production to changes in relative prices. Therefore, in the resource extraction sectors (col, gas, cru, and min) and the agriculture and forestry sector (agf) we include an additional top-level nest which combines the fixed factor with the capital-labor-energy-materials (KLEM) composite. The substitution elasticity between the fixed factor and KLEM composite is calibrated, so that the price elasticity of supply in these sectors matches empirical estimates.

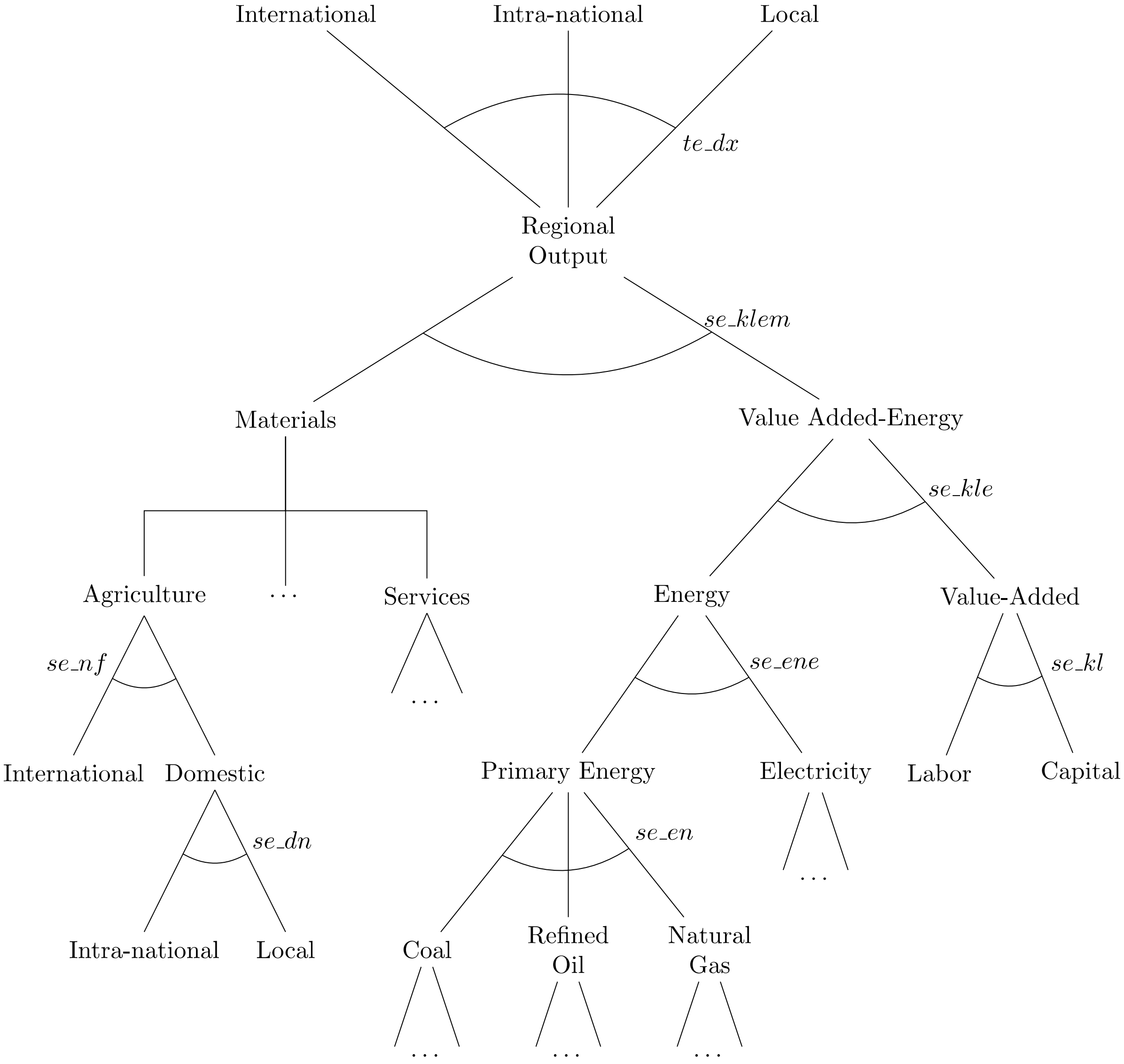

Figure 3: General Production Structure

Within each region, SAGE also models five representative households based on their income level in the initial year of the model (Table 2). The income groups are selected to match current U.S. income quintiles at a national level as closely as our underlying data source allows. Each representative household is assumed to maximize inter-temporal per capita welfare subject to a budget constraint and conditional on initial endowments of capital, fixed factor resources, and time. The inter-temporal welfare function is an isoelastic utility function (i.e., constant relative risk aversion), while intra-temporal preferences are modeled as a nested CES function (Figure 4).[11]

Table 2: SAGE Households

Household	Benchmark Year Income [2016$]
hh1	< $30,000
hh2	$30,000 - $50,000
hh3	$50,000 - $70,000
hh4	$70,000 - $150,000
hh5	> $150,000

The nested structure of the intra-temporal utility function treats energy and materials in a similar fashion to the standard production function. Households choose their relative consumption of primary energy sources before selecting the ratio of primary energy to electricity. The energy bundle is then traded off against non-transportation final consumption goods, a bundle that is then traded off against transportation. At the top level of the intra-temporal utility function the ratio of consumption to leisure is selected.

The inter-temporal connection between periods in the model occurs through the capital stock carried over from one period to the next. The growth of the capital stock is a function of the depreciation rate and endogenously determined investment. We assume a putty-clay specification for capital to more appropriately represent the mobility of extant capital across sectors. Production associated with existing capital at the start of the model’s time horizon is modeled as Leontief based on the initial year’s cost shares, while production with new capital has the substitution possibilities afforded in the nested CES

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[11] For regulatory analysis, the Federal government does not specify a social welfare function, which would be required to be able to explicitly integrate equity considerations into a benefit-cost analysis. In this paper, welfare is also not adjusted to equity weight or otherwise account for differences in income.

structure presented in Figure 3 New capital stock is considered perfectly mobile across sectors, while existing capital has limited and costly mobility as captured by a CET function that supplies extant capital across sectors. The exception is any sector associated with a fixed factor, such as the resource extraction or agriculture sectors. In those sectors, we do not model production from extant capital, and instead directly calibrate the own-price supply elasticity to empirical estimates through the substitution elasticity between the KLEM composite and the fixed factor.

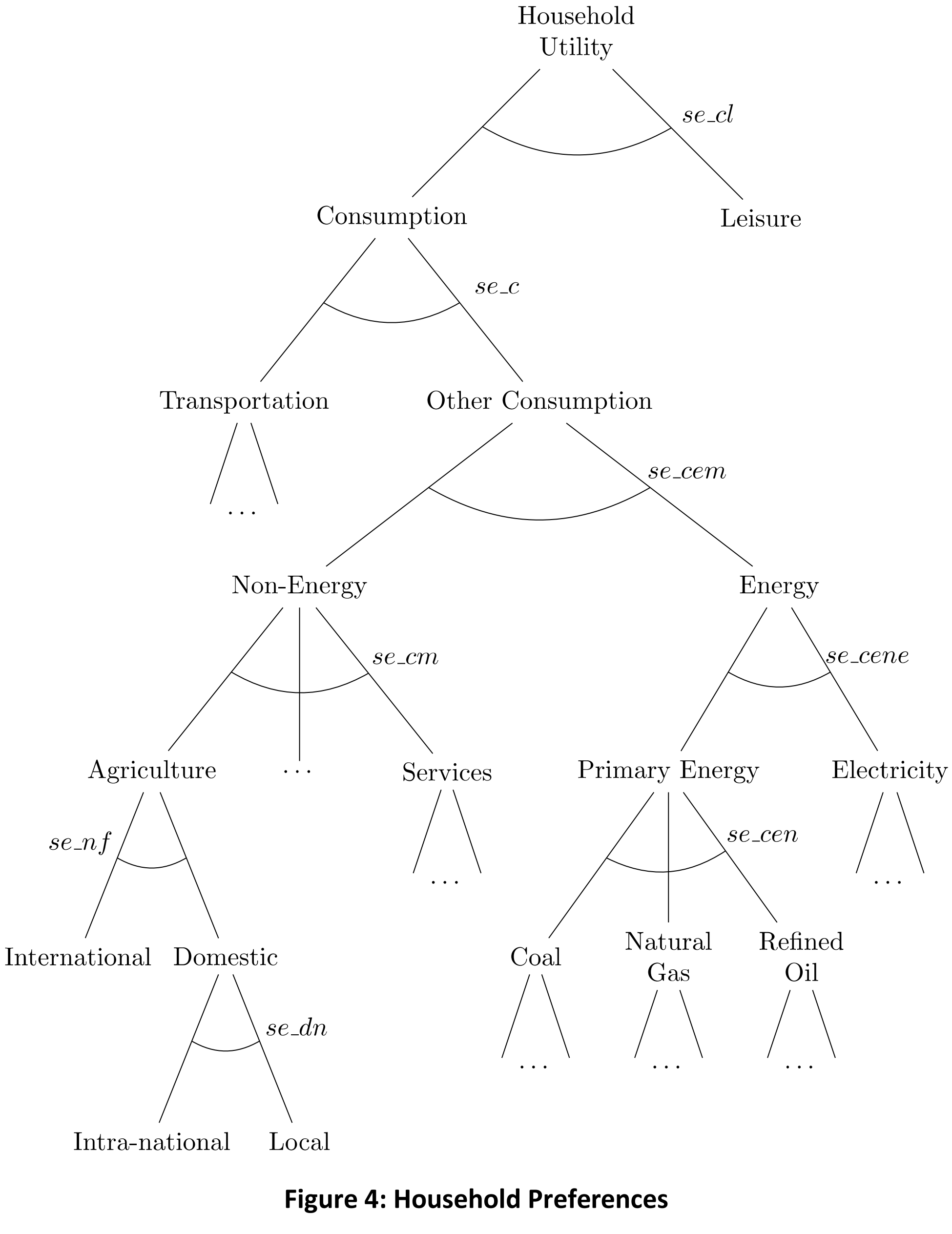

Figure 4: Household Preferences

SAGE has a single government agent representing all jurisdictions. The government raises revenue through ad valorem taxes on capital, labor, production, and consumption. Real government expenditures are assumed to grow at the balanced growth rate, based on population and productivity growth. The government balances its budget through lump sum transfers. The pre-existing tax on labor distorts the labor-leisure choice in the model by placing a wedge between the marginal value product of labor and returns earned by workers. The presence of broad-based consumption taxes has a similar effect by placing a wedge between the opportunity cost of production and consumption. Both effects lead households to reduce consumption and increase leisure relative to a first-best setting without distortionary taxes. The model includes a homogeneous tax on all capital returns, which places a wedge between the marginal value product of capital and the value of savings thereby, introducing an intertemporal distortion that shifts consumption towards the present relative to what would be optimal absent taxation. In other words, the tax increases the amount a household would need to save to increase consumption in the future by a dollar.

There are three main types of inputs to the model: (1) the social accounting matrix describing the state of the economy in the initial year; (2) substitution elasticities that define opportunities to move away from the structure observed in the initial year; and (3) parameters defining the expected evolution of the economy in the baseline. These inputs are described in more detail in Appendix A.

We solve the model as a mixed complementarity problem (MCP) following the approach of Mathiesen (1985) and Rutherford (1995). The MCP approach represents the model as a series of zero-profit conditions, market clearance conditions, budget constraints, household first-order conditions, and closure rules. The problem is formulated in the General Algebraic Modeling System (GAMS).[12] The MCP is solved using the PATH solver (Ferris and Munson, 2000).

3.2 Modeling Regulations

A large literature examines the GE implications of market-based greenhouse gas mitigation policies (e.g., Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1996; Dellink, et al. 2004).[13] In the United States, environmental regulation rarely relies on market-based incentives. Instead, it is common for environmental regulations to resemble an emissions rate standard, specify the use of certain types of pollution control equipment, and/or require the alteration of production processes. Using a highly stylized

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[12] GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 24.2.3. Washington, DC.

[13] Recent work by Corradini, et al. (2018), Böhringer, et al. (2016), and Böhringer, et al. (2008) also use CGE modeling frameworks to examine how interactions between a market-based instrument such as a tradable emissions cap and other policies such as a subsidy to innovation or energy efficiency standards affect the social cost of reducing greenhouse gas emissions in the European Union.

GE model, Fullerton and Heutel (2010) illustrate the conceptual difference between a cap on aggregate emissions and a standard that limits emissions per unit of output or input. While both types of policies lead to an output substitution effect, the implicit subsidy to production in rate-based regulations reduces the incentive to abate pollution on the extensive margin leading to a small output substitution effect. In the case of a technology mandate that effectively fixes emissions per unit of capital, firms have an incentive to invest more intensely in capital but less incentive to abate on the extensive margin. Goulder, et al. (1999) demonstrate that while these differences in policy design have a substantial effect on the social cost, the proportional impact of the tax interaction effect is relatively similar across emissions taxes, performance standards, and technology mandates.[14]

In this paper, we interpret regulatory requirements as mandates that a sector use more inputs to produce the same amount of output, particularly given the aggregated nature of the sectors we consider. For this reason, we focus our analysis on the additional inputs to production required for compliance and abstract away from how general equilibrium effects may influence the compliance strategy within the regulated sector afforded by more flexible regulatory designs. Building on prior work, we model the additional inputs required to comply with environmental regulations as productivity shocks in the regulated industry (e.g., Hazilla and Kopp, 1990; Pizer and Kopp, 2005; Pizer et al., 2006). One potential pitfall of this approach is that the substitution possibilities across inputs to pollution abatement match those of the regulated sector. The alternative is to model a separate pollution abatement sector with unique substitution elasticities. Since pollution abatement is not a well-defined activity within the national accounts, and there is a dearth of available information regarding the inputs to abatement activities and how they respond to changes in relative prices, we do not pursue this strategy. An advantage of this approach is that it is possible to move away from a Hicks neutral shock to examine the potential GE impacts of regulations requiring a different but more expensive composition of inputs (i.e., process changes).

In most cases, analysts engaged in a rulemaking process have an engineering-based cost estimate available that indicates what additional inputs are required based on baseline levels of production valued at baseline prices. Such an estimate can also be used to inform how to introduce a regulation into a CGE model. Given the exploratory nature of our analysis, we don’t have the luxury of detailed engineering estimates. As a base case, we therefore use the input requirements associated with past compliance activities for U.S. environmental regulations. Nestor and Pasurka (U.S. EPA, 1995) established input values

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[14] Goulder, et al. (1999) find that the tax interaction effect can be substantially higher for policies that generate scarcity rents not captured by the government and used to reduce pre-existing distortions.

for pollution abatement activities to comply with U.S. air pollution regulations. Since air pollution regulations make up a large proportion of regulations, in terms of volume and costs, this provides a reasonable starting point.[15] However, it has been shown that the results of CGE analyses of regulations can be sensitive to this assumption (e.g., Nestor and Pasurka, 1995), so we test the sensitivity of results to a Hicks'-neutral input share case, along with capital- and labor-only cases as a bounding exercise.

In many cases, environmental regulation may not affect all firms in an industry equally, which introduces heterogeneity in the burden across space, capital vintages, or production processes, among others. Given the exploratory nature of our analysis, as a base case we assume that each unit of production in the regulated sector faces the same level of pollution abatement expenditures. In other words, in each modeled year the engineering estimate of regulatory costs is spread across regional and capital vintaged production based on their share of national sectoral output in the baseline. We conduct sensitivity analysis by considering vintage differentiated regulations that affect only new or extant capital as a proxy for regulations that target new or existing sources.[16]

In our base case, we consider a regulation that is estimated to have compliance costs of $100 million per year. This is the threshold at which Executive Order 12866 requires a formal benefit-cost analysis. As it is not uncommon for air regulations to require resources in excess of this level (i.e., many are within the $1 billion to $3 billion range), we evaluate the sensitivity of our results to the size of the regulation (as measured by the value of the engineering estimate of compliance cost). While there are a variety of reasons why the costs of abatement may change over time, we keep the annual cost of a given sector-specific regulation constant.[17] In addition, we consider the sensitivity of our results to key parameters that characterize factor markets as well as assumptions about the temporal structure of the model.

The social cost of environmental regulation is measured using the equivalent variation (i.e., the maximum amount of money a representative agent is willing to pay in the initial year to forego the burden of the

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[15] Appendix B provides a mapping of the Nestor and Pasurka (1995a) cost shares to the commodities in our model.

[16] It is also possible that a regulation may only target specific sub-sectors subsumed within a more highly aggregated sector as defined in SAGE. We do not explore the sensitivity of the GE to engineering cost ratio to this type of partial regulation.

[17] Learning-by-doing, incentives to innovate, and economies of scale are all possible reasons why a plant's abatement costs may decrease over time. However, EPA regulatory analyses rarely make assumptions about the dynamic effects of the policy on abatement costs. Fischer and Newell (2008) find that different types of renewable energy policies (e.g., tax, subsidy, performance standard) vary in the extent to which they encourage learning, research and development, and knowledge spillovers. Amir, et al. (2008) show that it is theoretically possible for innovation due to environmental policy to shift the marginal abatement curve upward or downward.

regulation).[18] We compute this household-specific value numerically as the difference between the present value of baseline expenditures and those associated with the optimal path of consumption and leisure that would lead to the same level of inter-temporal welfare as the regulatory case but with prices fixed at their baseline values.[19] Aggregate social costs are determined by summing EV across the representative households in the model.

It is worth noting a few caveats with respect to the scope of study. Our focus in this paper is on the social cost of environmental mandates relative to engineering cost estimates and does not consider how the beneficial impacts of environmental regulation may affect equilibrium or interact with costs. Implicitly, we assume that the beneficial impacts of regulation are additively separable in households' utility functions. However, the beneficial impacts of pollution abatement could affect equilibrium in the economy through multiple channels (Williams, 2002; Carbone and Smith, 2008). Regulations that result in morbidity reductions for labor force participants or their children (i.e., reducing the amount of time parents take off from work), can increase productivity and have economy-wide impacts through the labor market (Matus et al. 2008; Mayeres and van Regemorter, 2008). While most mortality risk reductions from environmental regulations are associated with an older population typically out of the labor force, change in life expectancy can have meaningful economy-wide impacts through effects on savings decisions (Marten and Newbold, 2017). Pollution reductions can also directly impact on-the-job productivity of workers or reduce the depreciation rate of capital. It is possible that these beneficial impacts interact with costs of environmental regulations in meaningful ways. For example, increased demand for capital to comply with regulations may have a different impact on relative prices if it is occuring simultaneously with increased savings due to improved life expectancies. The magnitude and direction of these interactions remains an open and important question for future research.

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[18] An alternative measure of changes in social cost is compensating variation (CV). CV measures how much a consumer would need to be compensated to accept changes in prices and income such that the consumer achieves the same level of utility as prior to the policy. Because changes in consumer welfare encompass more than just market activities, welfare changes are typically measured as changes in EV or CV in CGE models (EPA 2015). While it may be important to report changes in GDP, it should not be mistaken as a measure of social cost, as it does not capture changes in non-market assets such as leisure, can result in double counting since investment today results in a stream of future consumption benefits, and may actually result in the wrong sign at least with regard to welfare. See SAB (2017) for a detailed discussion.

[19] The environmental regulations considered in this paper are relatively marginal changes, such that computing household-specific willingness-to-pay as the change in full consumption (consumption plus leisure) evaluated at benchmark prices produces the same results as using EV that would also take into account the curvature of the utility function and therefore, the differences in baseline income levels across households.

Similarly, we do not account for the way in which the single-sector environmental regulation we model may interact with other negative externalities. Just as an environmental policy may interact with pre-existing tax distortions by either exacerbating or ameliorating the deadweight loss associated with those taxes, it may interact with other pollution externalities not directly targeted by the regulation. Baylis, et al. (2014) demonstrate that, depending on their design, environmental policies can shift production and consumption in ways that both exacerbate and ameliorate the deadweight loss of pollution externalities not directly targeted by the policy.[20] Being able to capture such interactions in a consistent manner is an advantage of applying a GE framework, though studying the magnitude and direction of the effects is outside the scope of our study.

4 Results

In Section 4.1 we present results comparing compliance cost and GE social cost estimates in both a first- and second-best setting. In Section 4.2 we explore the sensitivity of social costs to regulatory structure, while in Section 4.3 we explore the sensitivity of our results to the magnitude of the regulation. In Sections 4.4 and 4.5 we test the sensitivity of our results to key parametric and structural modeling assumptions.

4.1 Drivers of General Equilibrium Cost Estimates

There are two primary reasons GE costs are expected to differ from engineering cost estimates in an ex ante setting. First, engineering costs do not account for how firms and households change behavior in response to regulation. The increased cost of production due to compliance with the new regulation is passed onto the consumer, at least in part, in the form of higher prices, which leads to a lower quantity of a commodity being produced and purchased (the output substitution effect). The general equilibrium demand curve that helps determine the output substitution effect will depend on substitution possibilities between inputs to production in the un-regulated sectors, imports and domestic production, consumption of different final goods, labor and leisure, and consumption across time. Second, engineering costs do not account for the interaction of the new regulation with pre-existing distortions in the economy, notably

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[20] Baylis, et al. (2014) impose a sector-specific carbon tax in a two-sector GE model where each output is produced by CO_2 emissions and a clean input. Two emissions leakage effects are identified: (1) an output effect, which results in positive leakage because households substitute away from the taxed to the untaxed good; and (2) an input substitution effect, which results in negative leakage as firms substitute away from emissions and into the clean input. The overall net effect on emission leakage is determined by the relative magnitude of these two effects.

taxes that fall mainly on inputs to production.[21] To understand the significance of these effects, including the relative roles of the tax interaction and output substitution effects, we conduct a series of experiments. These experiments rely on the same basic regulatory scenario but examine four different approaches to raising revenue in the model: all taxes are kept at their baseline (default) levels, all taxes are set to zero, only the labor tax is set to zero, and only the capital tax is set to zero.[22] In each case the regulation is assumed to have an ex ante engineering based cost of $100 million [2016$] in the initial year, affect all facilities (new and existing) within a sector, and grow proportional to output in the regulated sector. The regulation is imposed as a productivity shock where the cost shares for the abatement technology are based on the work of Nestor and Pasurka (U.S. EPA, 1995). For each tax scenario, we run the model 21 times varying the sector on which the regulation is imposed.[23]

Figure 5 presents the results from these illustrative analyses. Each row in the figure represents an analysis of a separate sector-specific regulation that imposes $100 million in compliance costs directly on that sector. Each point along a given row represents the percent difference between the GE costs and engineering costs for an individual regulation. A point on the zero line would indicate that the GE cost estimate is equal to the engineering compliance cost, while a point to the left (right) of that line represents a GE cost estimate that is less (greater) than the engineering cost estimate.

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[21] Accounting for imperfect competition in some sectors may also be relevant for determining social costs but is outside the scope of our analysis. To examine the implications of trade liberalization in the agricultural sector, Roson (2006) explored three alternative ways of representing imperfect competition (i.e., varying whether profits in the baseline are endogenous, whether to allow economies of scale, how to calibrate initial profits, and whether the number of firms is fixed). He found that the results are quite sensitive to the specification used with aggregate welfare impacts even switching signs across treatments. Balistreri and Rutherford (2012) explored the implications of a Melitz trade specification (which allows factors such as market size, technology and trade barriers to govern trade flows instead of an exogenous taste parameter) and found that it almost doubles the negative effect on output in energy-intensive, trade-exposed sectors relative to a standard trade specification.

[22] Real government expenditures are equal across all cases and the government's budget constraint is balanced through lump-sum taxes.

[23] We do not run the experiments for the services (srv) or healthcare services (hlt) sectors. The sectors are not a common focus of environmental regulations and are partially associated with tax-favored final consumption, which is not included in the model but may have important implications for social cost estimation (Parry and Bento, 2000).

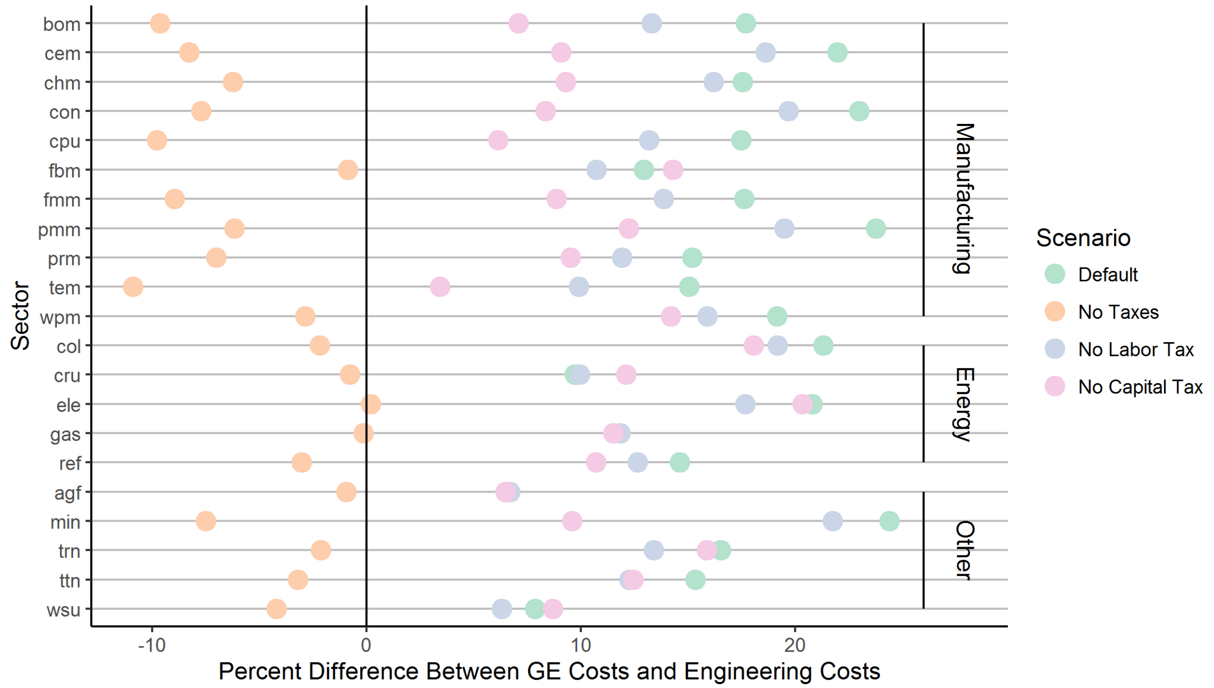

Figure 5: Role of Taxes in Defining General Equilibrium Costs

The case with no taxes demonstrates the impact of accounting for two types of GE interactions – substitution possibilities and economic linkages – on the estimated cost of regulation in a first best setting. Allowing consumers and producers the flexibility to change behavior in response to the policy lowers its estimated cost relative to ex ante compliance costs. For nearly all sectors, the cost savings from being able to substitute away from the regulated good outweighs any increases in the estimated cost that stem from accounting for economic linkages to other sectors (i.e., GE costs are generally to the left of the zero line)

A comparison of the first-best, no taxes case to the default case with all taxes set to their default levels, the second-best setting, shows how the tax interaction effect impacts the GE cost estimate across regulated sectors. In general, pre-existing distortions are a significant factor in determining the social cost of regulation, and, in fact, are the dominant effect when moving from an engineering-based to a GE-cost estimate. The GE cost estimates are around 15% to 25% higher than the engineering-based estimates for the majority of the 21 sector-by-sector regulatory scenarios.

When the output of a regulated sector is heavily used in investment, especially when a substantial portion of its domestic use is in the formation of new capital, the ratio of GE costs to engineering costs tends to be higher (i.e., at or above 20%). This is true for the construction (con), cement (cem), mining (min), and primary metal manufacturing (pmm) sectors. The pre-existing tax on capital increases the opportunity cost of savings and introduces an intertemporal distortion whereby the capital stock is less than would be optimal in a first best setting. When regulatory requirements increase the cost of producing goods and services important to the formation of capital that acts to raise the cost of new capital (i.e., the price of savings) relative to the cost of current consumption. Thus, regulations in these sectors interact more strongly with pre-existing capital taxes by having a greater impact on the capital stock (through savings) than regulations in other sectors. While somewhat difficult to see in Figure 5, removing the capital tax therefore has a substantially greater impact on the results in these sectors. It is worth noting that the formation of capital in our model is a Leontief technology based on benchmark input shares. This assumes no potential for the economy to adapt its capital formation process by shifting away from the regulated sector's commodity (e.g., shifting building materials), which may overestimate the capital tax interaction effect for these scenarios.

The electricity sector also exhibits a higher than average ratio of GE to engineering costs. However, the tax interaction effect, measured by the difference between the default and no taxes scenarios, is notably smaller than in other sectors with larger GE costs. In this case the relatively large GE to engineering cost ratio is driven by the lack of substitution opportunities for electricity and its ubiquitous use, leading to relatively inelastic demand for the commodity. Thus, there is no notable output substitution effect to place downward pressure on the GE costs, which would help to offset a portion of the tax interaction effect.

The sectors where the percentage difference between the GE and engineering costs is relatively low (i.e. at or just below 15%) also merit discussion. The water, sewage, and other utilities (wsu) sector tends to be associated with final demand, which likely leads to lower cross price elasticities and less interaction with distortionary taxes. Other sectors that exhibit smaller GE to engineering cost ratios – agriculture and forestry (agf), crude oil extraction (cru), and natural gas extraction (gas) – do not end up as final consumption in significant quantities, if at all. In these cases, there are a multitude of factors that, when taken together, lead these sectors to have low cross price elasticities compared to other sectors.

Figure 5 also presents two interim cases, one in which labor taxes are excluded and a second where capital taxes are excluded from the model. We include these cases to compare the relative influence of each of these distortions in the general equilibrium cost estimates. As has been previously demonstrated (e.g., Fullerton and Henderson, 1989), and is also the case in SAGE, the marginal excess burden (MEB) of capital taxes is greater than that of labor taxes (in SAGE the MEB for the capital tax is 15% higher than for the labor tax). Therefore, a regulation that results in a relatively greater reduction in the quantity of capital in the economy will have a greater tax interaction effect than one that mainly influences the quantity of labor supplied, all else equal. As a result, the capital tax interaction effect tends to have a greater impact on the GE cost estimates than the labor tax interaction effect. However, the relative role of the tax interaction effects differs across the directly regulated sectors. Regulations targeting the production of commodities that are heavily used, either directly or indirectly, in the formation of capital will place upward pressure on the relative price of new capital and therefore, tend to have the largest capital tax interaction effects (e.g., construction (con), cement (cem), mining (min), primary metal manufacturing (pmm), and transportation equipment manufacturing (tem)). Regulations in other sectors will still interact with the pre-existing capital tax through changes in the real rate of return to capital. However, when little to none of the regulated sector's output is directly used in the formation of capital it will have a smaller effect on the relative price of new capital and the capital tax interaction effect will tend to be of the same order of magnitude as the labor tax interaction effect (e.g., electricity (ele), crude oil extraction (cru), water, sewage, and other utilities (wsu), and agriculture and forestry (agf)).

While this series of experiments illustrate the general impact of different taxes, it offers limited ability for detailed quantitative comparisons. When an entire tax is removed from the model the baseline may be different in ways that affect the social costs of the policy. For example, removing the capital tax will increase savings and reduce near-term consumption in the baseline. As a result, regulations on sectors that primarily produce final consumption goods (e.g., water, sewage, and other utilities (wsu) or food and beverage manufacturing (fbm)) will represent a higher per unit compliance cost in the case without capital taxes leading to higher social costs than the default case, which would naturally have a small capital tax interaction effect for regulations in these sectors. Thus, while this exercise illustrates the relative importance of different taxes, it does not represent a true decomposition analysis that identifies the specific tax interaction effects that cumulatively determine the social cost in the default scenario.

4.2 Sensitivity of GE Costs to Regulatory Design and Implementation

While economic linkages, substitution possibilities, and interactions with pre-existing distortions cause the GE costs to differ significantly from ex ante engineering costs, those effects may be sensitive to key features of the environmental regulation. In this section, we explore the sensitivity of the GE cost estimates from Section 4.1 to two aspects of regulatory design and implementation: vintage differentiation (i.e., which sources are affected), and the input composition of the compliance technology or activity used to meet the standard.

U.S. environmental regulation often varies the stringency of a standard according to the vintage of the affected sources (e.g., new versus existing sources only). To explore the sensitivity of the GE cost estimates to this feature, we examine three different cases for each of the 21 sector-by-sector regulatory scenarios where the regulation only affects new sources, only affects existing sources, or affects all sources (the default case illustrated in Figure 5). To approximate a case where only new sources are affected, we impose compliance costs only on production associated with new capital in the regulated sector. For the case where only existing sources are affected by the regulation, we impose compliance costs only on production associated with extant capital in the sector. In each case, we hold the cost of the regulation per unit of output constant independent of the vintage of the affected sources.[24]

We allocate pollution abatement costs across input shares in four ways: (i) based on data compiled by Nestor and Pasurka (U.S. EPA, 1995), (ii) in the same proportion as sectoral production shares, i.e. Hicks-neutral, (iii) to labor inputs only, and (iv) to capital inputs only. The results presented in Figure 5 were generated using input shares based on data on U.S. air regulations from Nestor and Pasurka (U.S. EPA, 1995). Previous studies (e.g., Hazilla and Kopp, 1990; Jorgenson and Wilcoxen, 1990) often allocated abatement costs in Hicks-neutral proportions or to capital and labor only. Nestor and Pasurka (1995) demonstrated that the results from pollution control simulations performed using shares based on Hicks-neutral technology or allocations to labor and capital only could be significantly different from those performed using empirically based shares.

The Hicks-neutral allocation assumes that actions taken to comply with regulatory requirements do not change the proportion of labor, capital, or other inputs used in production. We also allocate abatement costs entirely to either capital or labor inputs (e.g., Ballard and Medema, 1993). By looking at cases where the pollution abatement activity is assumed to require only labor or capital we are able to examine the GE effects for regulations whose inputs are heavily biased towards one factor, compared to the case where compliance requires both capital and labor simultaneously. While our prior is that many regulatory requirements are capital-intensive, a recent National Association of Manufacturers survey suggests that around two thirds of regulatory compliance costs are associated with labor (Cain and Cain, 2014).

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[24] We hold abatement costs constant across capital vintages to test the sensitivity of GE costs to regulations that affect a fixed capital stock versus a more flexible capital stock. However, the motivation for focusing a regulation on new sources can be due to technical limitations that make pollution abatement costlier at existing sources, in which case the difference in cost between new and existing source regulations may differ. However, we note that vintage differentiation in regulations can often be motivated for non-technical reasons (see Stavins (2006) for a review).

Table 3 presents the percentage differences between the ex-ante GE and engineering cost estimates by input composition and affected sources. The percentage differences are averages across model runs for 21 sectors, where each of these sectors is shocked sequentially. The standard deviation is presented in parentheses after the percentage difference.

Table 3: Mean Percentage Difference Between General Equilibrium Costs and Engineering Costs

	Affected Sources		
Input Shares	All Sources	New Sources	Existing Sources
Nestor & Pasurka	17% (5)	18% (6)	12% (1)
Hicks-Neutral	21% (5)	23% (6)	15% (1)
Capital Only	23% (5)	24% (6)	20% (1)
Labor Only	25% (6)	28% (8)	18% (1)

Differences between GE and engineering-based cost estimates are sensitive to both how pollution abatement activities are allocated across input shares and which vintages within a given sector are affected. The ratio of GE to engineering-based costs are larger for the capital- and labor-only allocations than for the data driven and Hicks-neutral allocations.[25] This difference is primarily due to how the production taxes included in the model affect the regulatory scenarios. In each scenario we calibrate the regulatory shock to the same level of compliance expenditures but vary the input composition of those expenditures. While intermediate inputs used for compliance are ultimately produced by primary factors, their purchase price includes tax payments in additional to the value of the underlying resources.[26] Therefore, a regulation requiring $100 million worth of additional labor or capital expenditures will ultimately require a greater level of primary resources than a regulation requiring $100 million worth of additional intermediate input expenditures. This difference is not captured in engineering cost or partial equilibrium analyses and highlights a benefit of using a GE approach to capture the opportunity cost of regulations.

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[25] A scenario that requires a combination of capital and labor but no intermediate inputs will result in GE to engineering cost ratios very similar to a weighted average of the capital- and labor-only results with weights equal to the compliance shares.

[26] Some sectors on net receive a subsidy for production (e.g., water, sewer, and waste (wsu)) but they are mainly final consumption goods and not heavily used as intermediate inputs for compliance in any regulatory scenario.

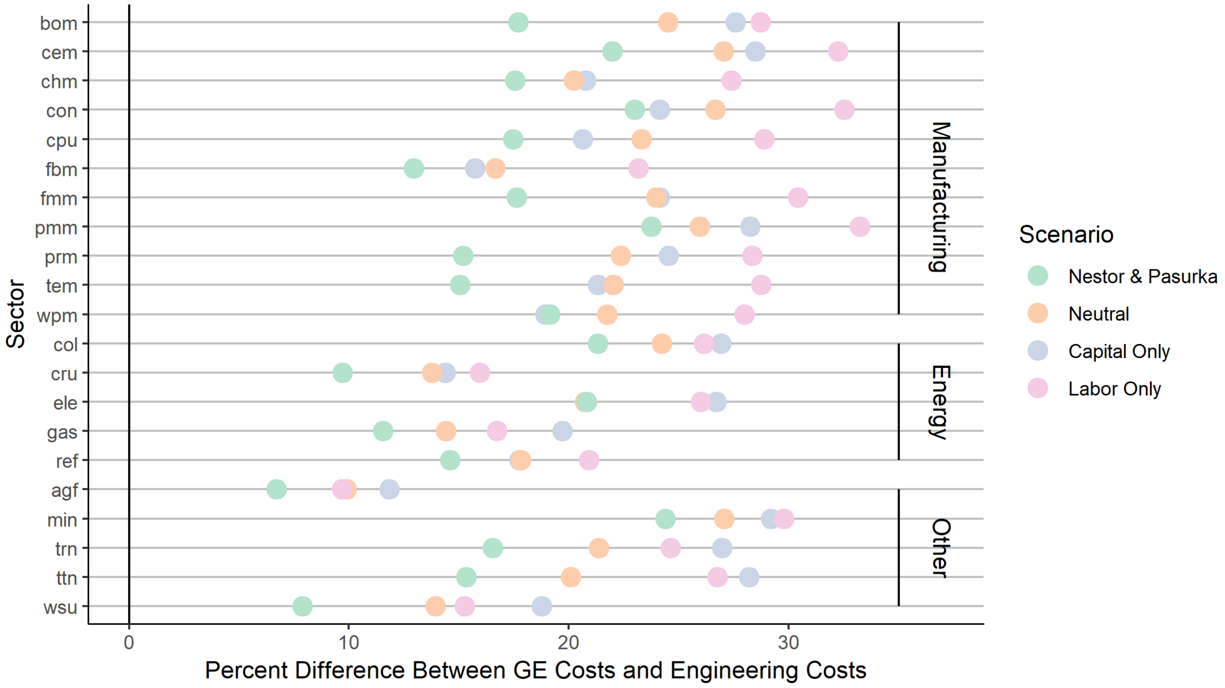
While production taxes explain most of the difference in social costs between the labor- or capital-only scenarios for a given sector, differences in implicit production-side substitution possibilities can also play a role when compliance requires intermediate inputs. Since production is assumed to be mobile across regions, additional requirements for intermediate inputs to satisfy compliance requirements can be meet with increased regional production, domestic imports, or foreign imports. However, since labor is assumed to be immobile across regions of the United States, any labor required to comply with the new regulation must be taken away from other production activities in the region or leisure. Capital, once installed, is also assumed to be immobile across regions, while savings is mobile across regions.

For the scenarios we examine, differences between the results for the data driven and Hicks-neutral allocations can be almost completely explained by differences in the amount of direct capital and labor expenditures required to comply with the regulation. In the Nestor and Pasurka allocation, 36% of the compliance expenditures are assumed to be directly for capital and labor compared to an average of 50% under the Hicks-neutral allocation.

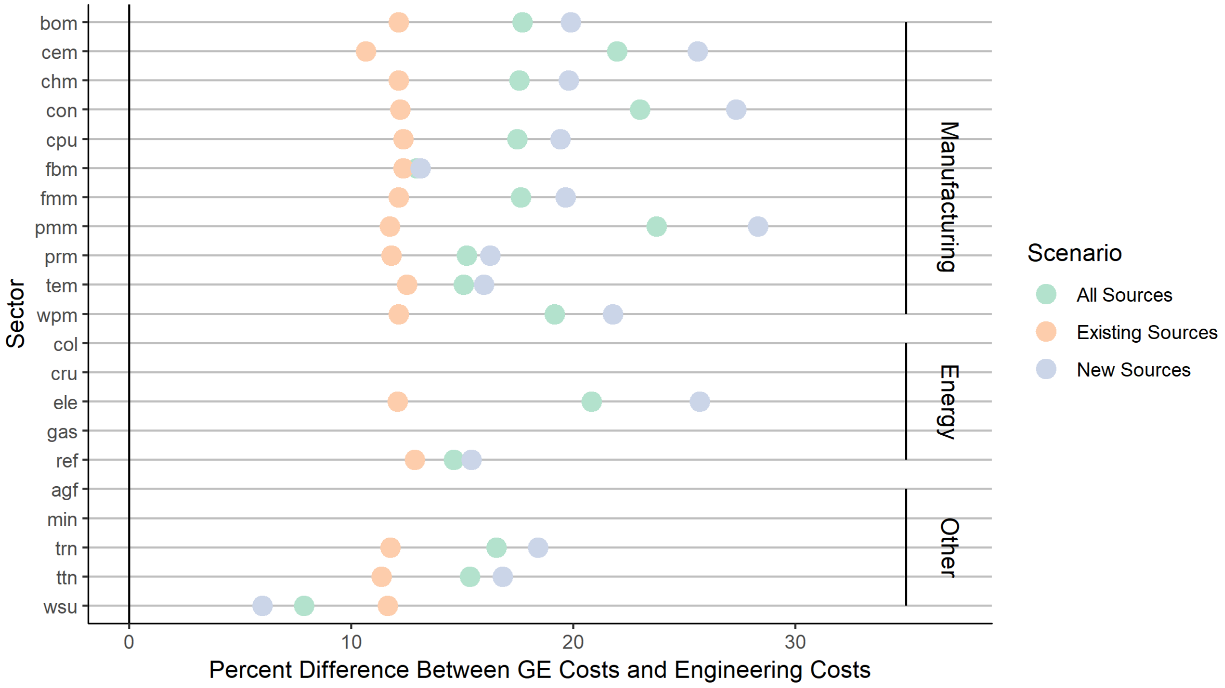
For a given input allocation, the difference between the GE and engineering cost estimates is also sensitive to vintage differentiation; though the results are similar when only new sources are affected compared to when all sources are affected. This is because new sources are ultimately responsible for the largest share of production over the simulation’s time horizon. When only existing sources are affected, the ratio of GE to engineering cost estimates are, on average, lower than both the all sources and existing only cases. Given the relatively fixed nature of existing capital, as characterized in our framework through the partial putty-clay specification, the existing source only regulation has a smaller effect on investment behavior for new capital and therefore a lower capital tax interaction effect.

While the average results presented in Table 3 are informative, they hide a great deal of heterogeneity across the regulated sectors. b. **Sensitivity of GE Costs to Affected Vintage**

Figure 6 shows the direction and magnitude that the input-share and vintage-based assumptions have on the percent difference between GE and engineering cost estimates. Recall that each row in the figure represents an analysis of a separate sector-specific regulation that imposes a per unit compliance cost directly on that sector, that if applied to all benchmark production in that sector would equal $100 million in compliance costs. Points along a given row represent the ratio of the GE to engineering costs for the four different input share assumptions in Figure 6a and for three different vintage assumptions in Figure 6b. When evaluating the impact of vintage differentiation, we return to our default input specification based on Nestor and Pasurka to improve readability of the plot. Other input allocations result in a similar pattern when the affected vintage is altered.



a. Sensitivity of GE Costs to Input Bias



b. Sensitivity of GE Costs to Affected Vintage

Figure 6: Sensitivity of GE Costs to Policy Specification

Across the 116 regulatory scenarios considered in Figure 6 the ratio of GE to engineering costs range from 6% to 33%. We can only identify a few relationships that seem to hold across all 21 regulated sector scenarios. First, as we saw previously, it appears that the percent difference between GE and engineering cost estimates is higher when compliance relies predominantly on primary factors. We also see that the GE to engineering cost ratio is roughly consistent across sectors for existing source-only regulations. This is due to the restricted production substitution elasticities in the model for existing sources. Further generalizations are difficult. However, vintage differentiation tends to have a slightly greater impact on the percent difference between GE and engineering costs for the manufacturing compared to the non-manufacturing sectors.

In general, the results in b. **Sensitivity of GE Costs to Affected Vintage**

Figure 6 suggest that the GE effects will be regulation specific and generalizations or rules-of-thumb for adjusting the compliance costs to better approximate social costs would not be robust. Furthermore, for most sectors the results from empirically informed Nestor and Pasurka cost shares are notably different than the Hicks-neutral specification and the capital- and labor-only allocations. This suggests that in practice care should be taken in determining the input composition of compliance activities to inform CGE modeling of regulations.

4.3 Sensitivity to Size of the Regulation

The expected cost of environmental regulations can also vary widely. The starting point for our analysis was a regulation with an engineering-based cost estimate of \$100 million in the initial year. This is the threshold at which Executive Order 12866 requires a formal benefit-cost analysis. However, out of the 26 air pollution regulations promulgated between 2003 and 2013 that had annualized compliance costs of \$100 million or more, eight were estimated to cost between \$500 million and \$1 billion annually, while another eight were estimated to cost over \$1 billion annually [2001\$] (OMB, 2014). No rule was anticipated to have compliance costs greater than \$10 billion annually.

As the cost of the regulation gets larger and induces greater substitution, the marginal cost of that substitution is expected to increase. This includes firms and consumers substituting away from the regulated sector's domestically produced output or firms in the regulated sector substituting away from relatively less productive inputs. As a result, the GE effects (substitution and tax interaction) are expected to decrease with the size of the regulation (Figure 7). For readability, Figure 7 presents the average change by major sector type. While there is some heterogeneity across the subsectors, the general trends remain consistent. We scale the results such that any change in the GE to engineering cost ratio is measured relative to a regulation with $100 million in compliance costs.

The general trend is a relatively minor decline in the ratio of GE to engineering costs as the absolute ex ante engineering cost estimate increases. For instance, a regulation in the manufacturing sectors with an initial year compliance cost of $2 billion has a GE to engineering cost ratio that is only about 1 percent smaller than a regulation with $100 million in compliance costs in the initial year. An exception is the case of sectors whose production functions exhibit decreasing returns to scale due to fixed factor inputs, such as in the fossil fuel extraction sectors. Because the fixed factor input requirement limits the substitution possibilities in the production process for these sectors, they exhibit a steeper decline in the GE to engineering cost ratio as the size of the regulation increases, though the effect remains relatively small (i.e., around 5 percent when moving from $100 million in initial year compliance to $2 billion in initial year compliance costs).

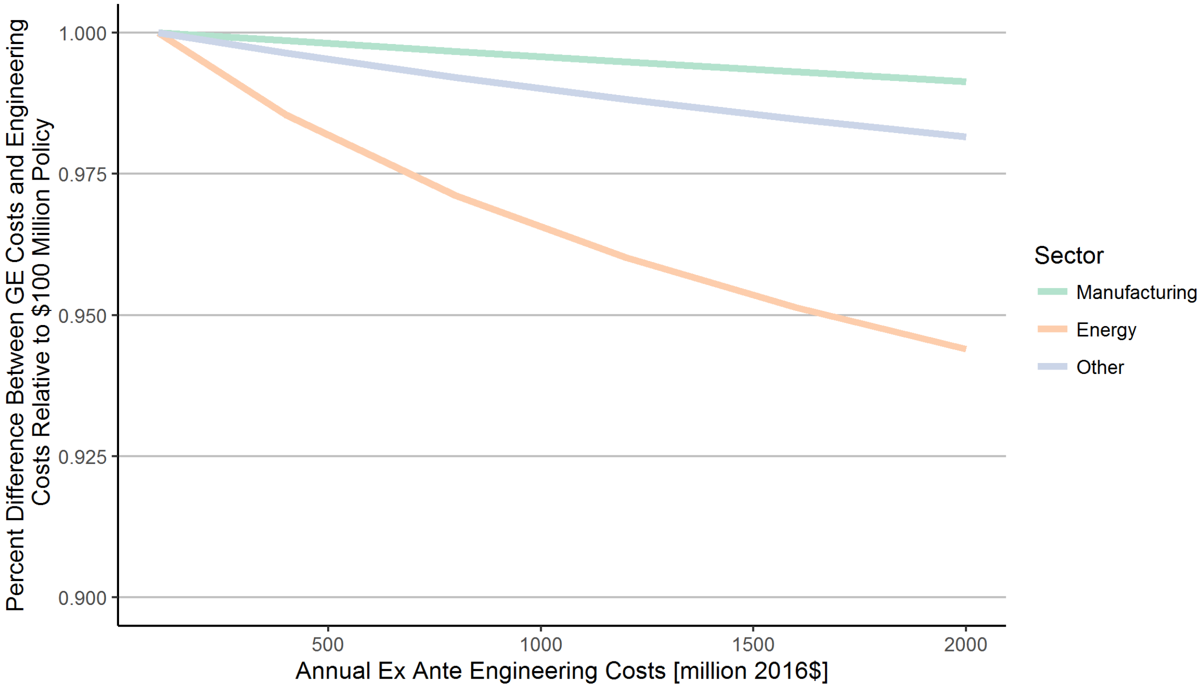


Figure 7: Sensitivity of GE Costs to Size of Policy

4.4 Sensitivity to Factor Market Characteristics

Model structure and parameter assumptions have long been recognized as important drivers in applied CGE analysis. We are particularly interested in parameters that help determine the supply and demand curves in factor markets, as these are of first-order importance in determining the magnitude of the tax interaction effect. Previous CGE analyses have shown that results are sensitive to labor supply and saving assumptions (Shoven and Whalley, 1984), the elasticity of substitution between labor and capital (Fox and Fullerton, 1991), and uncertainty around elasticity parameter assumptions (Elliot et al., 2012). These were found to be more important than other assumptions such as the level of detail included about the U.S. tax system or the benchmark social accounting matrix (Fox and Fullerton, 1991).

The sensitivity of CGE model results to parameter values has been the subject of much discussion given the common approach of selecting values through calibration (Hansen and Heckman, 1996). Selecting econometrically estimated parameter values from the literature is not without its own concerns due to inconsistencies between the structure of the CGE model and a large range of potentially contradictory empirical analyses that provide elasticity estimates (Shoven and Whalley, 1984; Canova, 1995). In response, some researchers have chosen to econometrically estimate model parameters in a framework that is structurally consistent with the CGE model (e.g., Jorgenson et al., 2013). While taking such an approach is beyond the scope of this paper, we examine the sensitivity of our results to key parametric and structural assumptions in our model. We focus on the labor supply elasticity, value-added substitution elasticity, and the representation of extant capital as our results are most sensitive to parameters and assumptions affecting the supply and demand of primary factors.

The labor supply elasticity defines the sensitivity of households' labor-leisure choice to changes in the real wage and is therefore, a key factor driving the marginal excess burden of labor and capital taxes, and their tax interaction effects. One review of empirical studies found that estimates for the compensated labor supply elasticity ranged from 0.1 to 0.3 (McClelland and Mok, 2012). The default compensated labor supply elasticity in SAGE is set to the midpoint of this range (0.2).[27] To test the sensitivity of our results to this assumption we consider two alternatives: perfectly inelastic labor supply, essentially a labor supply elasticity of zero; and more elastic labor supply, where we set the compensated labor supply elasticity to 0.4, a value above the range in McClelland and Mok (2012), but that has sometimes been used in applied CGE analysis (e.g., Goulder, et al. 1999; EPA, 2008).

Figure 8 presents the results of the labor supply elasticity sensitivity for our base case using the Nestor and Pasurka input shares and assuming all sources are affected by the regulation. In general, the direction

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[27] Using the separate ranges provided by McClelland and Mok (2012) for men and single women and for married women, and weighting by labor force share also leads to a midpoint of approximately 0.2.

of the results is as expected. With perfectly inelastic labor supply the regulation does not affect the level of labor supplied in equilibrium, thereby limiting the interaction with the labor tax. As such, the results with perfectly inelastic labor supply are similar to the results without a labor tax in Figure 5. With a more elastic labor supply the regulation induces a larger response in the labor market resulting in a larger tax interaction effect causing the percentage difference between GE and engineering cost estimates to increase to around 25-35 percent for most sectors.

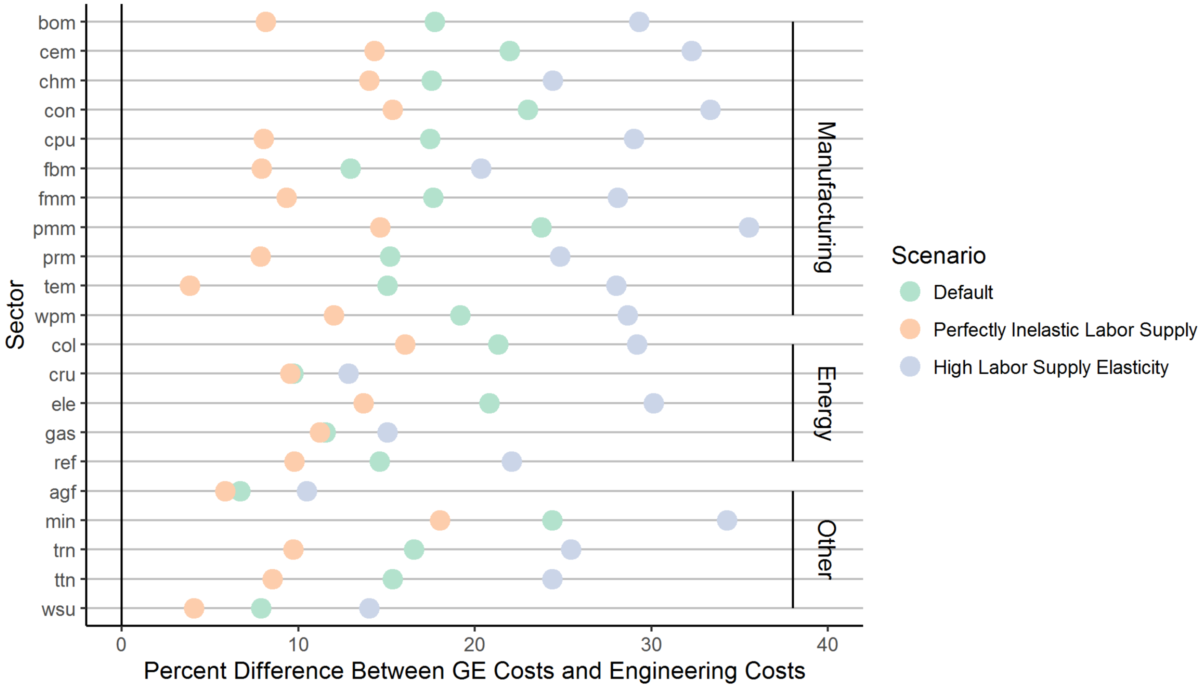

Figure 8: Sensitivity of General Equilibrium Costs to Labor Supply Elasticity

In general, the sensitivity of the results to changes in the compensated labor supply elasticity are roughly equivalent across sectors. The GE to engineering cost ratio is around 9 percentage points higher on average with the high compensated labor supply elasticity and is around 6 percentage points lower on average with perfectly inelastic labor supply. Notable exceptions are the sectors associated with fixed factor resources in the model, such as agriculture and forestry (agf), crude oil extraction (cru), and natural gas extraction (gas).

The tax interaction effect will, in part, depend on the shape of the labor and capital demand curves which are largely determined by the value-added substitution elasticity, *se_kl*. The values for *se_kl* are mainly adapted from the econometric estimates of Koesler and Schymura (2015). We test the sensitivity our results to this specification by considering a low and high value-added substitution elasticity defined as minus/plus one standard deviation. We also consider the case of a unit elasticity (Cobb-Douglas specification) as this assumption has been commonly applied in the literature (e.g., Manne et al. 1995; Bohringer and Rutherford, 1997; Paltsev et al. 2005). Figure 9 presents the results of the value-added substitution sensitivity analysis using the Nestor and Pasurka input shares and assuming all sources are affected by the regulation. In each case we change the *se_kl* parameter for all sectors, not just the directly regulated sector in a given simulation.

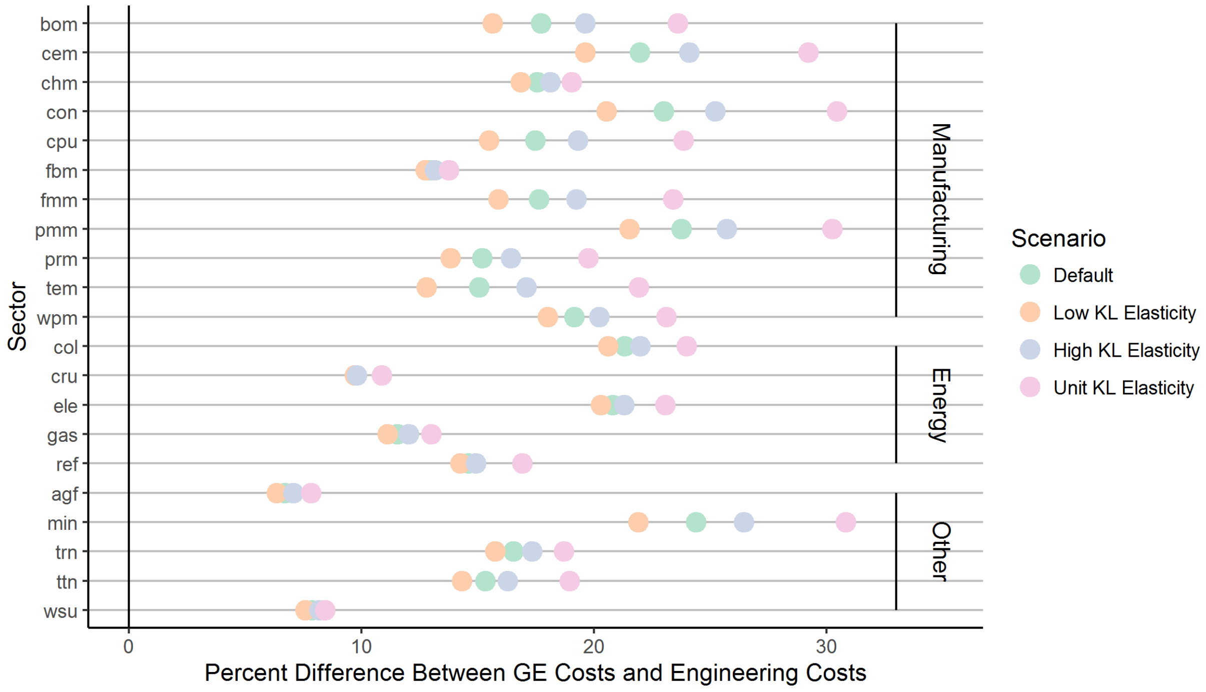

Figure 9: Sensitivity of General Equilibrium Costs to Value Added Substitution Elasticity (*se_kl*)

For many sectors, the results are not very sensitive to the specification of the value-added substitution elasticity. On average, setting the value-added substitution elasticity one standard deviation lower reduces the GE to engineering cost ratio by around 1 percentage point, while setting the elasticity one standard deviation higher increases the ratio by around 1 percentage point. Manufacturing sectors show slightly greater sensitivity to the specification of the value-added substitution elasticity.

When we instead use the unit value-added substitution elasticity (i.e., Cobb-Douglas specification), the GE to engineering cost ratio is around 4 percentage points higher on average. For most sectors the default value of *se_kl*, and even a one standard deviation increase, is well below unity, such that the increase in the ratio of GE to engineering costs under the Cobb-Douglas specification is as expected. For the few cases where the default value of *se_kl* is slightly higher than unity, in agriculture and forestry (agf), electric utilities (ele), and water, sewer, and other utilities (wsu), the Cobb-Douglas specification still yields higher estimates of the GE to engineering cost ratio. This is a result of the increased factor demand response in the non-regulated sectors due to the significantly higher value-added substitution elasticity in those sectors. But in general, the results are robust to specific assumptions about *se_kl* and are more sensitive to assumptions regarding the uncompensated labor supply elasticity.

The marginal excess burden of pre-existing tax distortions depends, in part, on the ability to substitute other production inputs, including labor, for capital and the ability to shift capital across sectors in response to a shock. In in addition to *se_kl*, the putty-clay specification for new versus existing capital has a notable role in defining the available substitution possibilities for capital.

There are two main approaches to modeling the capital stock in dynamic CGE models: “putty-putty” and “putty-clay” (Phelps, 1963). The “putty-putty” approach assumes an undifferentiated capital stock that is fully malleable and moves instantaneously (and thus, without cost) between sectors of the economy. In contrast, the “putty-clay” approach differentiates between new investment, which is fully malleable across sectors, and existing capital, which is sector-specific and costly to repurpose. When there are constraints on the movement of capital across sectors, a regulation that requires new capital to meet emission requirements will result in transition costs as outdated technology is retired and replaced or as existing capital is moved across sectors (Pizer and Kopp, 2005). The inclusion of capital constraints also slows investment in new technologies because they must compete with existing technologies for which there is no alternative use (McFarland et al., 2004).

To test the sensitivity of our findings to the treatment of capital we compare the base case results that assume “putty-clay” capital with the case where all capital is perfectly malleable independent of vintage. Figure 10 presents the results of this sensitivity analysis using the Nestor and Pasurka input shares and assuming all sources are affected by the regulation. The average change in the ratio of GE to engineering costs from allowing capital to be fully malleable regardless of vintage is around 1 percentage point. In general, the results are robust to the treatment of capital and are more sensitive to assumptions regarding the uncompensated labor supply elasticity.

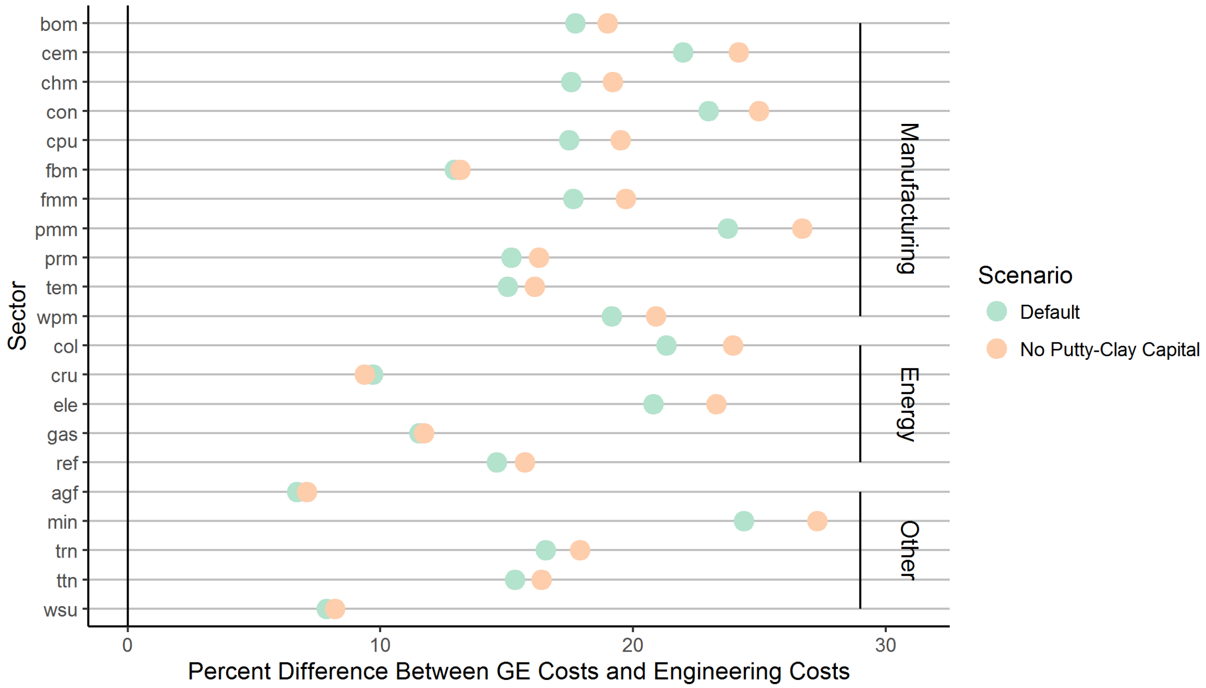

Figure 10: Sensitivity of General Equilibrium Costs to Capital Mobility

4.5 Sensitivity to Temporal Structure of the Model

Regulatory analyses of environmental polices conducted by the EPA are often static and consider the social cost of a regulation at a given (future) point in time. Such estimates provide snapshots of the expected costs for firms, government, and households but do not allow for behavioral changes from one-time period to affect responses in another time period. However, effects over time may be important when investment in capital to comply with the regulation in one period affects investment decisions in future periods. Pizer and Kopp (2005) note that static productivity losses from environmental regulations are amplified over time due to their effect on capital accumulation (a lower capital stock over time reduces economic output and therefore welfare). Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) have also shown that this effect is potentially significant.[28]

To test the sensitivity of our findings to the temporal specification of the model we compare our results to those generated from a relatively equivalent static model. The static version of the model is based on the characteristics of the initial year in the model (i.e., 2016). In other words, it does not represent any

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[28] This conclusion is based on large-scale changes in environmental regulation. Hazilla and Kopp (1990), and Jorgenson and Wilcoxen (1990) examine the combined welfare effects of the 1972 Clean Water and 1977 Clean Air Acts.

population, labor productivity, and energy intensity growth characterized in the dynamic model. Furthermore, capital is fully malleable in the static model and the real level of investment is held constant at the baseline value. All other aspects of the model are consistent with the default dynamic version.

Figure 11 presents the results from both the dynamic and static versions of the model for our base case using the Nestor and Pasurka input shares and assuming all sources are affected by the regulation. In most cases the ratio of GE to engineering costs is lower for the static version of the model, consistent with previous studies, and the fact that the static version of the model misses the social costs associated with altering the accumulation of capital. However, there is large variation in the impact of capturing dynamics depending on the regulated sector. The GE to engineering cost ratio is significantly higher (10 to 15 percentage points) for sectors whose output is predominately used in the creation of physical capital, for example construction (con), primary metal manufacturing (pmm), cement (cem), mining (min).

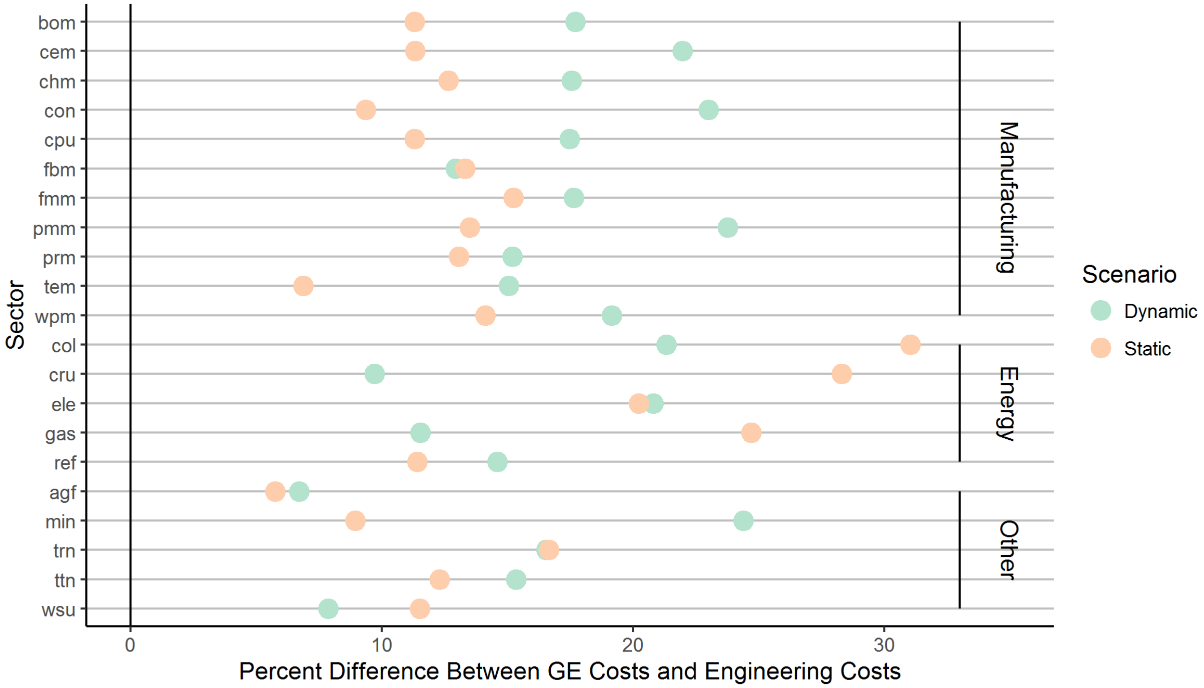

Figure 11: Sensitivity of General Equilibrium Costs to Temporal Specification

In some cases – coal mining (col), crude oil extraction (cru), and natural gas extraction (gas) – the GE to engineering cost ratio is lower in the static model compared to the dynamic model. In the baseline of the dynamic model, energy intensity of production and consumption is falling over time and the economy is increasingly moving away from primary fuel use towards electricity in production consistent with the U.S. Energy Information Administration's Annual Energy Outlook. The static version of the model does not pick up this transition and therefore, the ratio of GE to engineering costs for regulations targeting the fossil fuel extraction sectors is notably higher than in the dynamic model.

5 Concluding Remarks

The potential for significant errors when engineering costs are used to approximate general equilibrium social costs has been well established in the theoretical economics literature. However, in practice engineering or partial equilibrium cost estimates continue to remain the predominant focus of regulatory analysis. One reason for the continued neglect of GE effects in policy analysis are lingering questions regarding the magnitude of GE effects in standard regulatory applications.[29] We present results from a detailed CGE model comparing the difference between the social cost of environmental regulation and ex ante engineering estimates of compliance costs for standard regulatory applications, and explore the conditions under which GE analysis may add value in practice.

Our results demonstrate that even for small regulations both the output substitution and tax interaction effects are significant, and ex ante compliance cost estimates tend to substantially underestimate the social cost of regulation independent of the sector subject to regulation or the composition of inputs required for compliance. Specifically, we find that social costs for single sector environmental regulations can be 6% to 33% larger than engineering-based compliance expenditures depending on the regulated sector and input composition of compliance, based on our scenarios (see Figure 6). While direct comparisons are difficult, the magnitude of our results is generally in line with previous studies. In studying the cumulative impact of regulations promulgated under the Clean Air Act and the Clean Water Act, Hazilla and Kopp (1990) estimate that the GE social costs exceeded private compliance expenditures by 51%. While this difference is higher than our estimate, their focus is on the costs of multiple broad statutes that affect nearly every sector of the economy, resulting in potentially important interaction effects. Focusing only on the Clean Air Act but over a different time period, U.S EPA (2011) estimates that GE social costs exceeded compliance expenditures by 9%. A key difference with the U.S EPA (2011) study is that it assumes a significant share of compliance expenditures fall directly on households due to regulations in the transportation sector. This would be similar to our scenarios in which the regulated sector is primarily

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[29] In fact, the U.S. EPA recently convened an SAB panel of experts to consider, among other questions, the conditions under which GE analyses of prospective regulations add value on top of the engineering or PE analyses typically conducted. See https://yosemite.epa.gov/sab/SABPRODUCT.NSF/0/07E67CF77B54734285257BB0004F87ED

associated with final good production, which are at the lower end of the estimated range of GE social costs relative to engineering-based costs.

Goulder, et el. (1999) evaluate the additional cost of stylized environmental policies in the presence of pre-existing taxes on labor and capital income. For command and control policies, such as performance standards and technology mandates, they find that the tax interaction effect increases social costs by around 27%. We can derive a similar metric by comparing our "Default" results with the "No Taxes" scenario in Figure 5, where on average the tax interaction effect increases the social costs by 21%. While there are several differences between the studies, two stand out as particularly important. First, Goulder, et el. (1999) assume a compensated labor supply elasticity of 0.4 compared to our default value of 0.2. In our labor supply elasticity sensitivity (Figure 8) we find the higher labor supply elasticity increased the social cost estimates by 9% on average. Second, Goulder, et el. (1999) employ a static model. In our sensitivity analysis we find that employing a dynamic model increased the social cost estimates by 2% on average (Figure 11). The net of these two effects may, therefore, explain much of the difference.

Our results are robust across a larger set of regulatory scenarios and a series of sensitivity analyses that varied parametric and structural assumptions. We find that the details of the regulation under consideration can significantly affect the GE social costs and therefore generalizations about the bias of engineering cost estimates (beyond the direction of the bias) are unlikely to be robust. We also find that details about an abatement technology's input requirements have a significant effect on the GE social costs, such that simplified formulas for the excess burden of commodity taxes are unlikely to be robust in practice for determining the social costs of environmental regulations.

Despite these sensitivities, it is possible to glean insights as to when a GE analyses that is tailored to a specific rulemaking might add value for welfare analysis. First, when the net benefits based on engineering costs are relatively close to zero, particularly if compliance is capital or labor intensive, it may be important to conduct a CGE analysis to determine whether the GE effects substantively affect the magnitude and possibly the sign of the net benefits. Second, if multiple regulatory options are being considered and they differ significantly in their input composition, GE analysis can highlight potentially significant differences in their social costs by netting out transfers embedded in producer prices that can differ across inputs and would be implicitly included in engineering or partial equilibrium analyses. Third, the ratio of the social to engineering costs is not very sensitive to the size of a regulation. Therefore, all else equal, the size of the regulation may not be a good indicator of the relative importance of GE effects. That said, when a regulation is larger in magnitude the stakes are higher. Fourth, a regulation's interaction with pre-existing taxes on capital will be greater for sectors whose output is important for the formation of physical capital. It is worth noting that our study is focused on the conditions under which a GE analysis may add value in assessing the social costs of a regulation. We have not considered the potential GE effects that may be associated with the beneficial impacts of pollution reduction, although we recognize this as an important area for future research. It is also possible that a GE analysis may add value to an evaluation of incidence or other economic impacts of key interest even when the GE feedbacks don't have a significant bearing on the overall net benefits of a policy.

Our study is intended to be a broad look at the GE effects of environmental regulations and therefore, some simplifying assumption were made that should be revisited in a detailed policy analysis. For example, we consider regulations imposed on relatively aggregate sectors of the economy. Implicit in this assumption is that all commodities produced within an aggregate sector are perfect compliments. In cases where a regulation only affects a segment of a sector and for which the sector also produces close substitutes, such characteristics may have important implications for the GE effects. Likewise, we do not consider how abatement cost heterogeneity across regulated firms may affect social cost estimation. For some regulations, intra-sectoral substitution may be of first order importance in estimating social costs, although such effects are difficult to capture in CGE models. The SAB panel recommended that when firm heterogeneity is expected to be important, linking CGE and detailed PE sector models may provide useful insight (SAB, 2017).

Furthermore, we note that we have not considered all possible interactions between environmental regulations and market imperfections that may be relevant in estimating the overall welfare change in equilibrium. For regulations that target externalities associated with the production of commodities associated with high excise taxes, subsidies, or favored tax treatment, there may be additional tax interaction effects worthy of consideration. Interactions with other non-tax market interventions, such as other regulations may have relevant GE effects. In addition, our analysis does not consider additional non-tax market distortions with which a regulation may have interactions. Shifts in production and consumption patterns in response to regulation of a specific pollutant may result in changes in other pollutants or negative externalities. These interactions are akin to the tax-interaction effect and may also be of first order importance for applied welfare analysis.

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Appendix

A. Model Calibration

The social accounting matrix is built from the 2016 state level accounts in the IMPLAN dataset.[30] The IMPLAN dataset is extended in three ways. First, ad valorem taxes for labor and capital income are added to the dataset (consumption and production tax rates are taken from the IMPLAN dataset). Labor tax rates are the sum of observed payroll tax rates and average marginal income tax rates from a wage perturbation in NBER's TAXSIM model (Feenberg and Coutts, 1993). Marginal capital tax rates are taken from the U.S. values in Paltsev et al. (2005). Second, oil and gas extraction is disaggregated into separate sectors for crude oil extraction and natural gas extraction using state level data on production and consumption by sector from the U.S. Energy Information Administration and trade data from the U.S. Census Bureau. Third, we use population estimates for each representative household by region from the U.S. Census Bureau's Current Population Survey.

The substitution elasticities for the production functions and Armington trade specification are adopted from recent empirical studies. The three KLEM substitution elasticities (*se_klem*, *se_kle*, and *se_kl*) are adopted from Koesler and Schymura (2015), while the substitution elasticities for the energy bundle (*se_ene* and *se_en*) are adopted from Serletis, et al. (2010). The Armington elasticities between the local-intra-national composite and intra-national imports (*se_nf*) are adopted from Hertel et al. (2008). To calibrate the Armington elasticity between local and intra-national imports (*se_dn*) and the transformation elasticity between output destinations (*te_dx*) we follow Caron and Rausch (2013). The price elasticities of supply used to calibrate the substitution between the KLEM composite and fixed factors in resource extraction and agriculture sectors (*se_rklem*) are adopted from additional sources. For natural gas extraction, crude oil extraction, and coal mining we follow Arora (2014), Beckman et al. (2011) and Balistreri and Rutherford (2001), respectively. For agriculture and forestry, we follow the Hertel et al. (2002). In the intra-temporal utility function the substitution elasticity between consumption and leisure (*se_cl*), along with the benchmark time endowment, are calibrated to match the midpoint of the ranges for the compensated and uncompensated labor supply elasticities in the review of McClelland and Mok (2012).[31] We adopt the substitution elasticities in the intra-temporal utility function's energy bundle

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[30] IMPLAN Group, LLC, 16740 Birkdale Commons Parkway, Suite 206, Huntersville, NC 28078; www.IMPLAN.com .

[31] The calibrated compensated labor supply elasticity is 0.2 and the calibrated uncompensated labor supply elasticity is 0.5 based on the midpoints in McClelland and Mok (2012).

(*se_cene*, *se_cen*) from Serletis et al. (2010). The remaining substitution elasticities in the intra-temporal utility function (*se_c*, *se_cm*, and *se_cem*) are adopted from Caron and Rausch (2013), who use the same nested CES specification. The inter-temporal substitution elasticity of full consumption is adopted from Jorgenson et al. (2013). Additional details and specific parameter values are presented in Marten and Garbaccio (2018).

The exogenous parameters defining expectations about the growth and structure of the economy in the baseline are derived from U.S. Energy Information Administration's 2018 Annual Energy Outlook (AEO). Economic growth is driven primarily by population growth and Harrod neutral (i.e., labor embodied) productivity growth. Both of these parameters are set to the average growth rates over the time horizon of the most recent AEO. Energy intensity improvements are assumed to be capital embodied and calibrated by shifting the future cost shares in the nested CES production functions to match the sector specific average growth rates of energy intensity of production reported in the most recent AEO. Consumption shares in the intra-temporal utility function are similarly shifted away from energy goods to approximate the average reduction in the share of real consumption expenditures on specific energy types as reported in AEO. Finally, the share of coal in electricity production is shifted towards capital and labor, to match the shift from coal fired generation to renewables in AEO (noting that the share of electricity generation from natural gas is expected to remain relatively constant in AEO thereby not requiring additional calibration).

B. Regulation Input Bias Specification

Table 4: Alternative Input Shares for Abatement Technology

Input	Nestor and Pasurka	Capital Only	Labor Only
agf	--	--	--
cru	--	--	--
col	--	--	--
min	--	--	--
ele	0.270	--	--
gas	--	--	--
wsu	--	--	--
con	0.060	--	--
fbm	--	--	--
wpm	0.010	--	--
ref	0.010	--	--
chm	0.010	--	--
prm	0.025	--	--
cem	0.025	--	--
pmm	--	--	--
fmm	--	--	--
cpu	0.006	--	--
tem	0.001	--	--
bom	0.003	--	--
trn	0.010	--	--
ttn	0.010	--	--
srv	0.200	--	--
hlt	--	--	--
l	0.160	--	1.000
k	0.200	1.000	--