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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).[4] The value of extending a PE analysis to capture effects in other, related or indirectly affected sectors will depend on the magnitude of the relative price changes induced by the regulation. Using a highly aggregated six-sector 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 single-sector environmental policies could be relatively close approximations to the GE social costs, but that the PE welfare estimates were a poor approximation for multi-sector policies. Similarly, Hazilla and Kopp (1990) examined the impact of Clean Air and Clean Water Act compliance costs on the U.S. economy and estimated that sectors which bore no direct compliance costs could still experience output reductions of almost 5% in 1990. A 2011 study by the U.S. Environmental Protection Agency (EPA) found a similar result, in that the Clean Air Act Amendments may notably impact output in sectors with little to no direct regulation (US EPA, 2011).

Pre-existing distortions in the economy can also have first order effects on the social costs of environmental policies (e.g., Bovenberg and Goulder, 1996; Goulder et al., 1997; Goulder et al., 1999). Specifically, research has found that partial equilibrium cost estimates may differ significantly from general equilibrium costs due to interactions with pre-existing tax distortions (e.g., Bovenberg and deMooij, 1994; Bovenberg and Goulder, 1996; Lithgart and van der Ploeg, 1999; Fullerton and Metcalf,

[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.

2001; and Pizer et al., 2006), and that this may hold for relatively small single sector policies depending on the policy instrument (Goulder et al., 1999). This literature has largely focused on static analyses of single policies using analytical or highly stylized, aggregate numerical GE models. Murray et al. (2005), however, argue that interactions between regulatory compliance costs and tax distortions may be sensitive to key assumptions in this literature, and conclude that generalizations about the difference between compliance costs and social costs should be approached with caution.

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 results of Harberger (1964) imply that estimates of costs in the directly regulated market capture all social costs only when all other markets are undistorted and perfectly competitive. The SAB panel's advice added practical nuance to Harberger's insight, noting 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."

In this paper, we use a detailed computable general equilibrium (CGE) model to compare the difference between the social cost of environmental regulation 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.

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

[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. 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).

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, by itself, the size of a regulation is not a good indicator as to the value of a GE analysis. Second, when the benefit-cost ratio based on compliance costs is relatively close to one or compliance activities are capital or labor intensive, it may be important to conduct a GE analysis to determine whether the regulation is beneficial to society on net. Third, if multiple regulatory options are being considered and they differ significantly in their input composition, the tax interaction effect may be of first-order importance in determining the relative efficiency of the options, such that a GE analysis could be warranted. 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 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 that causes a contraction in the sector and which results in a deadweight loss 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 deadweight loss are a function of these GE effects (Goulder and Williams, 2003).[7]

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. Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) moved beyond these simple assumptions, developing econometrically-estimated, dynamic CGE models of the U.S. economy 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.

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).[8] 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.[9]

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[7] Goulder and Williams (2003) show theoretically and numerically that ignoring GE effects when calculating the excess burden from a commodity tax may significantly underestimate its distortionary effects. To estimate the labor market effects missed by standard excess burden calculations, they assume that what is taxed resembles the average good. If the taxed commodity is more or less substitutable for leisure than the average good or interacts with taxes outside the labor market, their estimate will misestimate the GE effects.

[8] If an environmental regulation affects wages such that individuals opt to work fewer hours, this exacerbates an already existing distortion in the labor market, since labor taxes already discourage individuals from working as much as they would otherwise, and has a welfare cost not captured by direct compliance cost estimates.

[9] 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

While there is theoretical and numerical evidence that GE effects may be of first-order importance for estimating the social cost of certain environmental regulations, concern has been raised about generalizing to other regulatory contexts (Murray et al., 2005). The difference between the GE estimates of social cost and engineering or PE estimates of compliance costs 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). The shape of the marginal cost curve in the regulated sector also has implications for the GE effects through its effect on the 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.

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.

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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.

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).

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

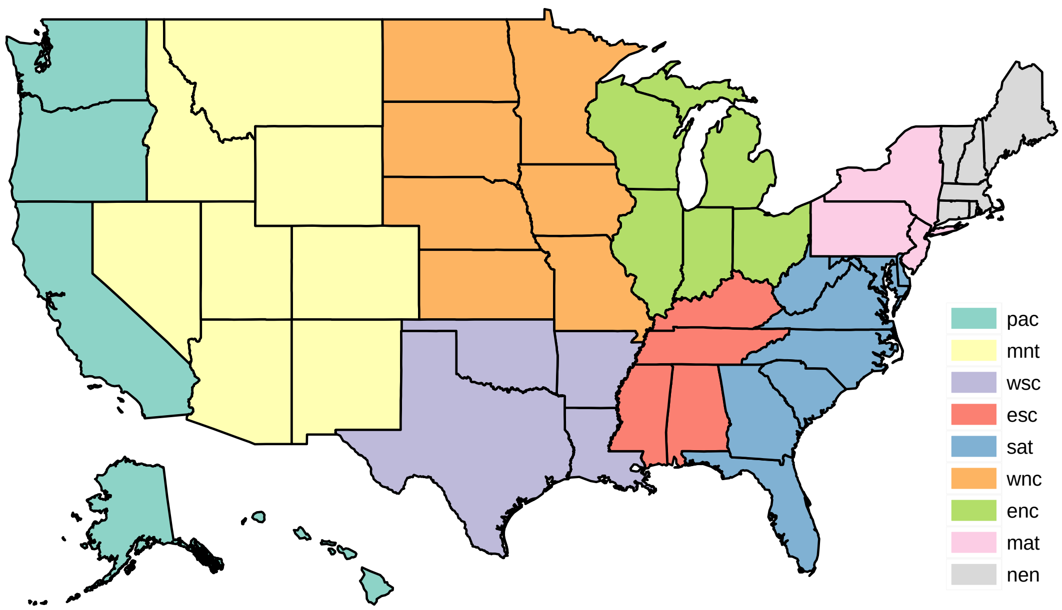

Figure 1: SAGE Regions

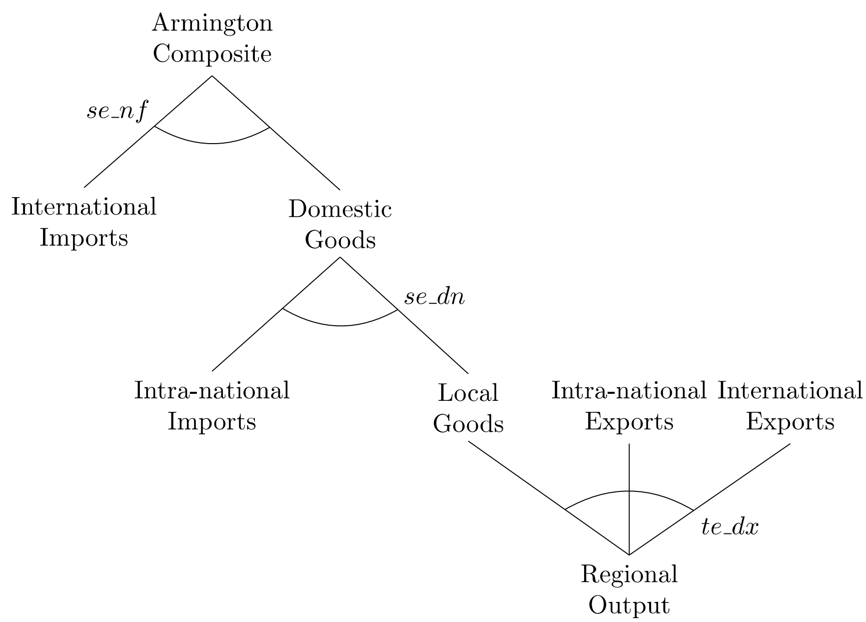

Figure 2: Armington Trade Specification

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.

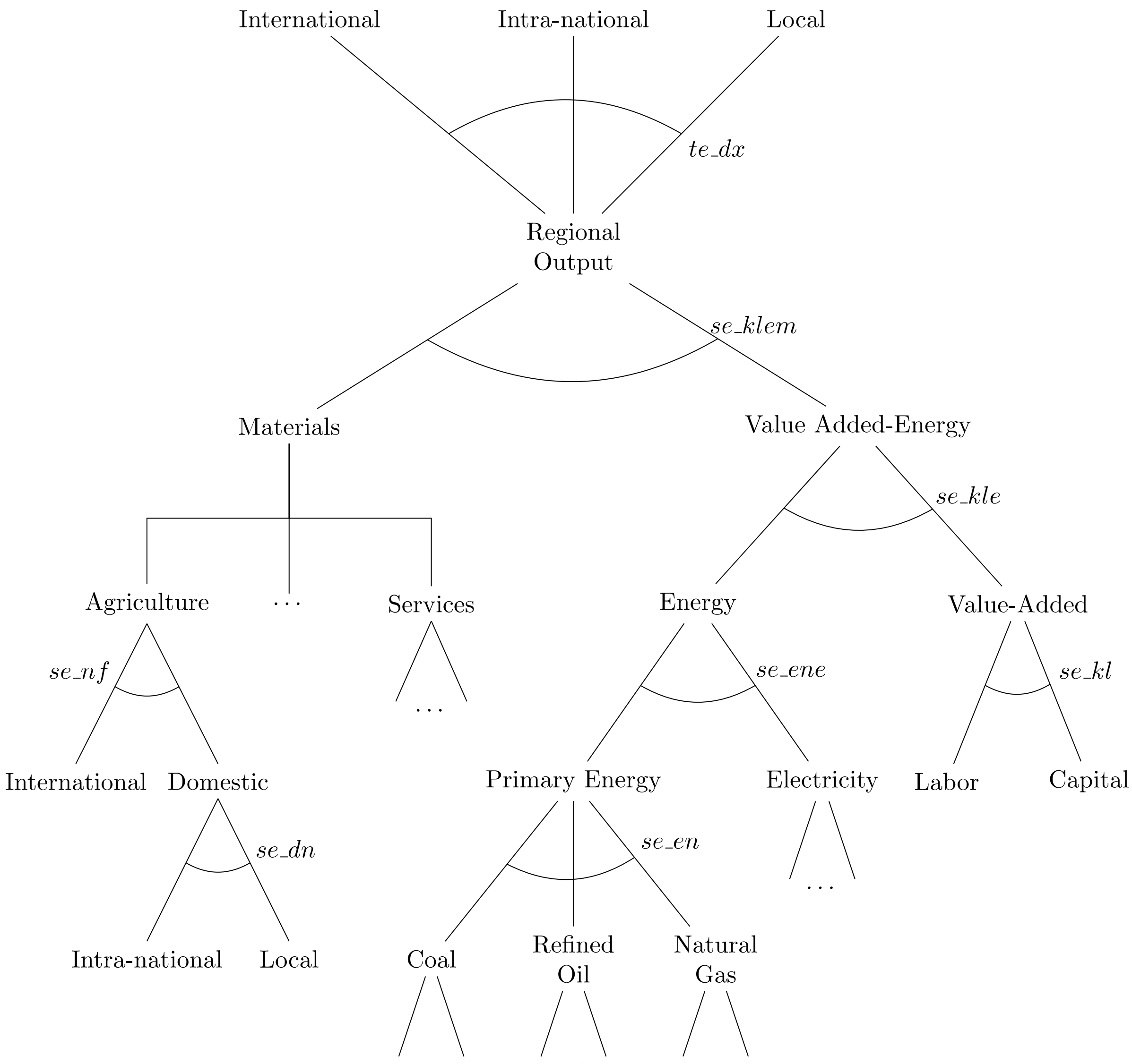

Figure 3: General Production Structure

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

[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.

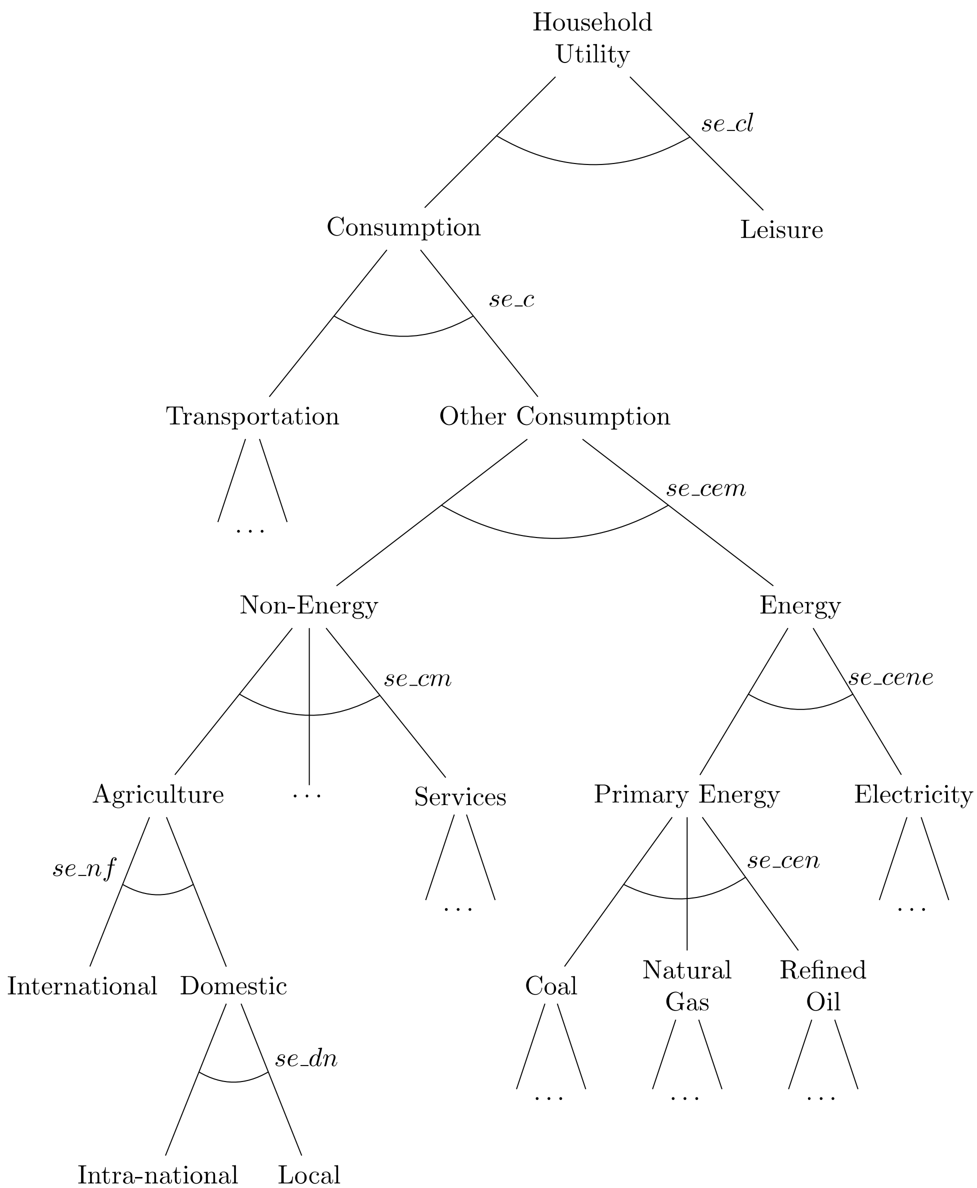

Figure 4: Household Preferences

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.

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). As carbon dioxide emissions are closely linked to fuel use, a carbon tax or cap-and-trade system is relatively straight-forward to represent in a CGE model. In the United States, however, 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. While modifying input use to reduce emissions is often incentivized by regulation, the output channel does not aid facilities in meeting regulatory requirements. Thus, regulatory requirements can often be interpreted 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 when afforded by more flexible regulatory designs.

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

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

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 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.[13] 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.

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.

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.[14]

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

[13] Appendix B provides a mapping of the Nestor and Pasurka (1995a) cost shares to the commodities in our model.
[14] 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.

measured by the value of the engineering estimate of compliance cost). 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 regulation).[15] We compute this household-specific value numerically by holding prices fixed at their baseline values and determining the value that, when subtracted from each representative agent's budget constraint in the initial period, would lead to the same level of inter-temporal welfare as they would have experienced under the regulation.[16,17] Aggregate social costs are determined by summing EV across the representative households in the model.

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

[15] 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.

[16] In the default version of the model representative agents are required to balance the budget constraint in each period and equivalent variation is computed as the amount of money they would be able to pay in the initial period to achieve the post-regulatory welfare level. The representative agents are aggregated enough that this approach provides approximately the same results as using inter-temporal budget constraints that allow for borrowing.

[17] 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.

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 taxes that fall mainly on inputs to production.[18] 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.[19] 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.[20]

Figure 5 presents the results from this decomposition analysis. 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 ratio of the GE costs to the 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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[18] A policy's interactions with other distortions, such as negative externalities or imperfect competition, may also be relevant for determining social costs but, as they are not reflected in the CGE model, they are outside the scope of our analysis.

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

[20] 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).

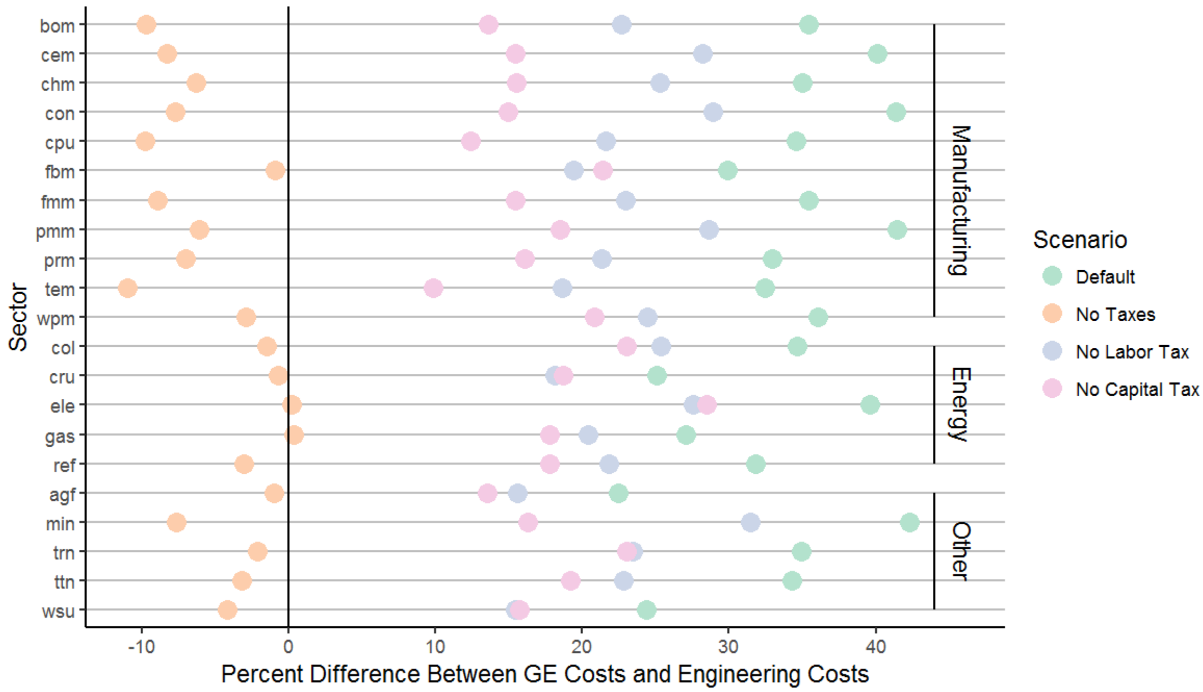

Figure 5: Role of Taxes in Defining General Equilibrium Costs

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 25% to 35% 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 (at or above 40%). This is true for the construction (con), cement (cem), mining (min), and primary metal manufacturing (pmm) sectors. Reducing the productivity of these sectors by requiring pollution abatement has a relatively greater impact on the cost of new capital, compared to when a regulation is implemented in other sectors, and thus provides a larger disincentive for investment. Thus, regulations in these sectors interact more strongly with pre-existing capital taxes. While somewhat difficult to see in Figure 5, removing the capital tax therefore has a greater impact on the results in these sectors. The electricity sector also exhibits a higher than average ratio of GE to engineering costs. Electricity is used as an intermediate input in all sectors of the economy and energy inputs are assumed to be a substitute for primary factors. As a result, increases in electricity prices due to regulation can result in a non-trivial shift the demand for primary factors increasing 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 25%, 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 if greater than that of labor taxes (in SAGE the MEB for the capital tax is 15% higher than for the labor tax). Therefore, regulation that results in relatively greater reductions 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. In the scenario where the labor tax is removed the ratio of GE to engineering cost estimates are around 11 percentage points lower on average than the default case, while in the scenario where the capital tax is removed the ratio is around 16 percentage points lower on average than the default case. 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 highest 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 any 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 tends 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)).

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, that effect may also 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. The most common cases are regulations that affect only new or only existing sources. 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.[21]

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,

[21] In some cases, the motivation for focusing a regulation on new sources can be due to technical limitations that make pollution abatement more costly 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).

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 better 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 in nature, a recent National Association of Manufacturers survey suggests that around two thirds of regulatory compliance costs are associated with labor (Cain and Cain, 2014).

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	34% (6)	36% (7)	29% (1)
Hicks-Neutral	35% (6)	37% (7)	27% (4)
Capital Only	70% (8)	71% (10)	64% (2)
Labor Only	72% (8)	76% (12)	63% (1)

It is immediately evident that the differences between GE and engineering-based cost estimates are much more sensitive to how pollution abatement activities are allocated across input shares than they are to which vintages within a given sector are affected. While the differences for the data driven and Hicks-neutral allocations are similar, they are significantly larger for both the capital- and labor-only allocations. As demonstrated by Fullerton and Heutel (2010), non-revenue raising environmental regulations can have significant effects on factor prices and in turn on real incomes. In our simulations, a productivity shock, regardless of the cost allocation across inputs, places downward pressure on real factor prices. When the abatement input requirements fall predominantly on primary factors, as illustrated by our capital- and labor-only simulations, the impact on the relative prices of the primary factors is greatest and consequently so is the tax interaction effect, which is the dominant driver in the difference between the GE and engineering cost estimates.

For a given input allocation, the difference between the GE and engineering cost estimates is less sensitive to vintage differentiation; the differences being very 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 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. 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 three different vintage assumptions, denoted by shape, and four different input shares assumptions, denoted by color.

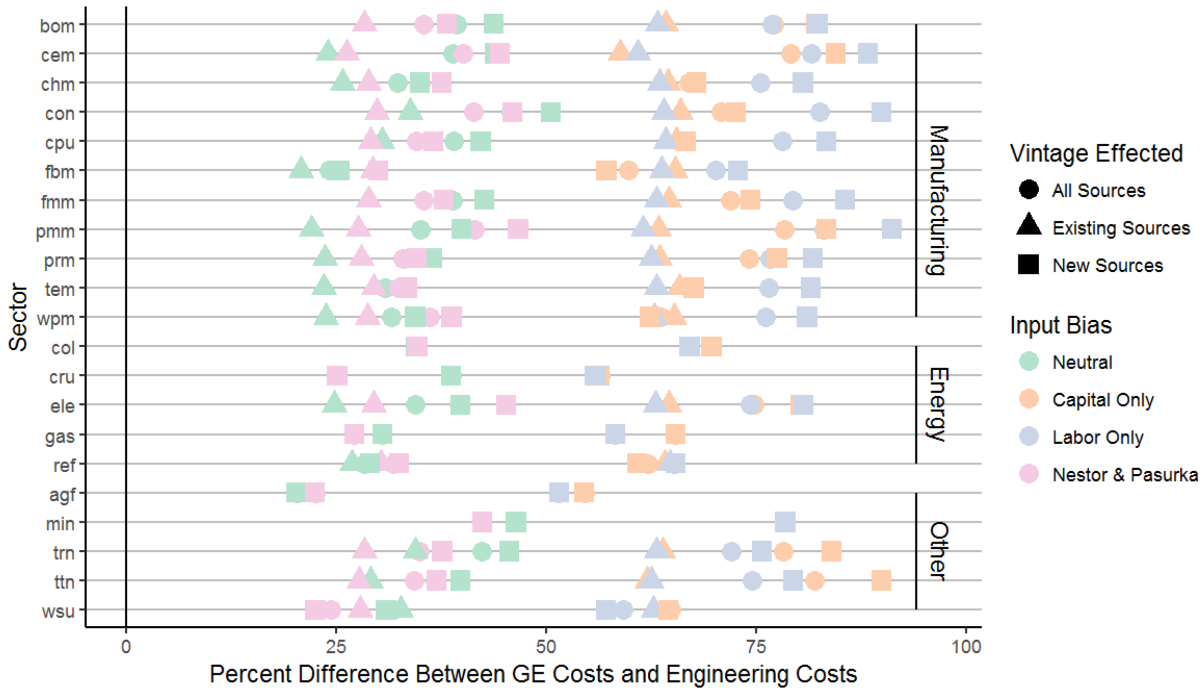

Figure 6: Sensitivity of GE Costs to Affected Vintages and Input Bias

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, for pollution abatement cost shares that are not sector specific (i.e., labor only, capital only, Nestor and Pasurka) 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.

Since the average difference across sectors is less than the standard deviation, further generalizations are difficult. That said, it is possible to identify several differences in the sensitivity of the GE to engineering cost ratio between the manufacturing and non-manufacturing sectors. For the manufacturing sectors, vintage differentiation tends to have a slightly greater impact on the percent difference between GE and engineering costs when the pollution abatement inputs are predominantly labor or capital based. This does not necessarily hold outside of the manufacturing sectors. Likewise, for manufacturing sectors the empirically informed Nestor and Pasurka cost shares are roughly consistent with the Hicks-neutral specification. For the energy and service sectors, the Nestor and Pasurka cost shares and Hicks-neutral cases produce significantly different results. In general, the results in 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.

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., 5 percent when moving from $100 million in initial year compliance to $2 billion in initial year compliance costs).

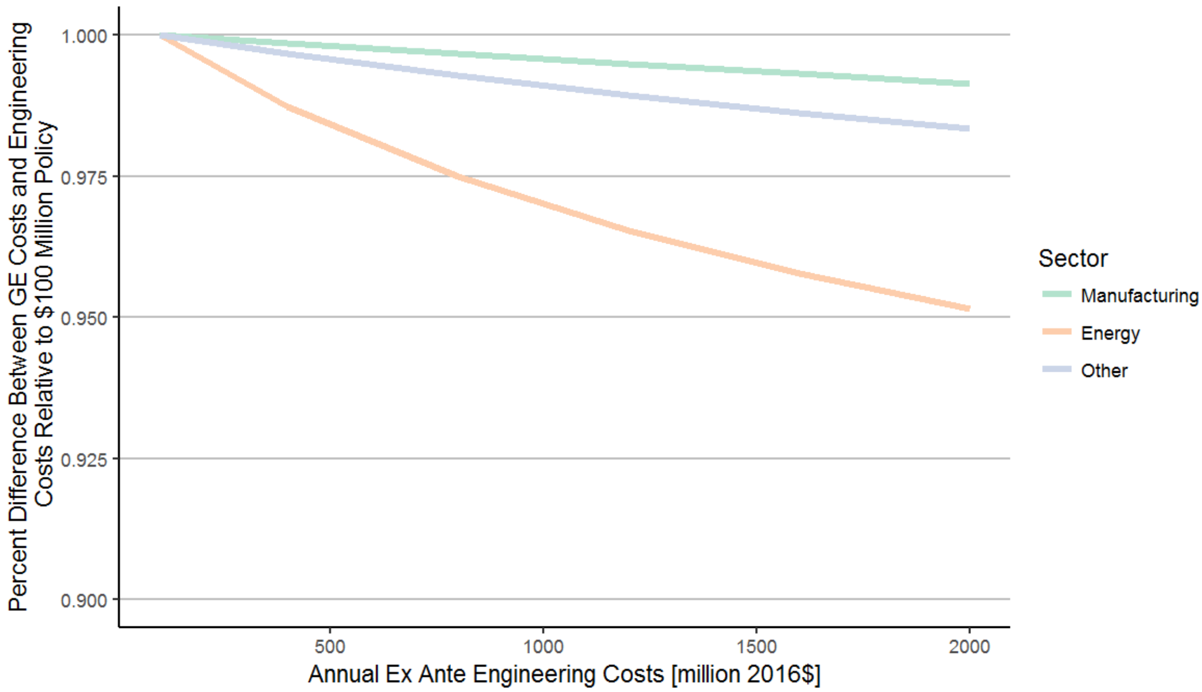

Figure 7: Sensitivity of GE Costs to Size of Policy

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).[22] 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 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 40 percent or more for most sectors.

[22] 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.

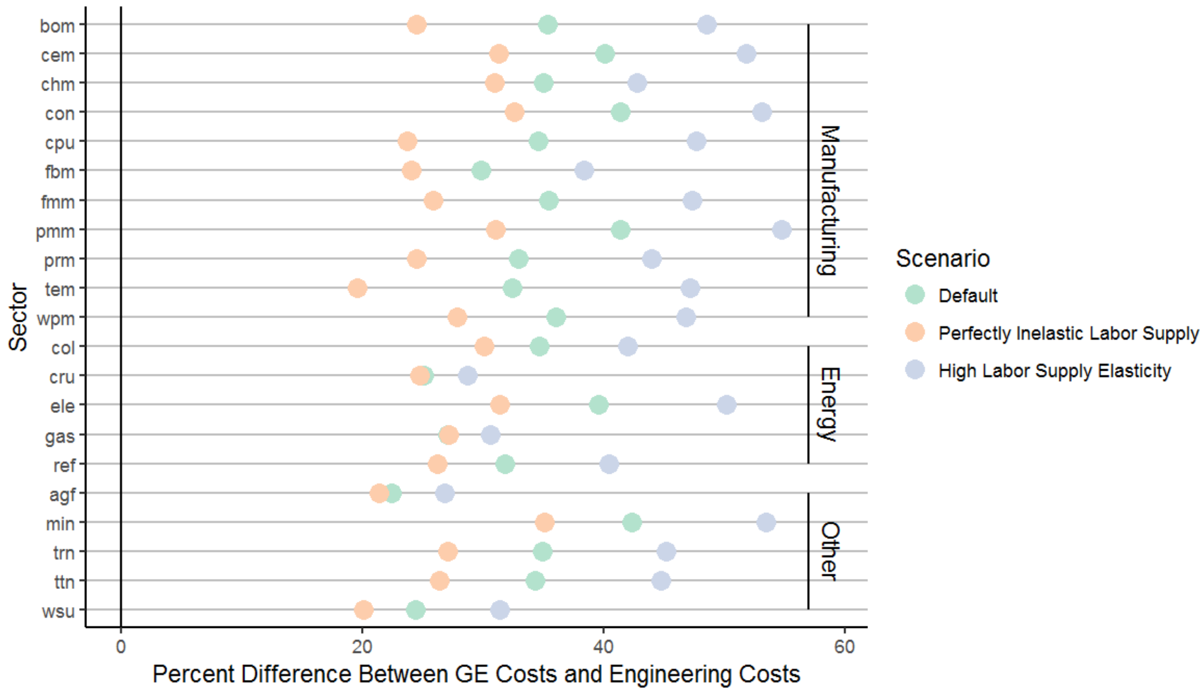

Figure 8: Sensitivity of General Equilibrium Costs to Labor Supply Elasticity

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 7 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.

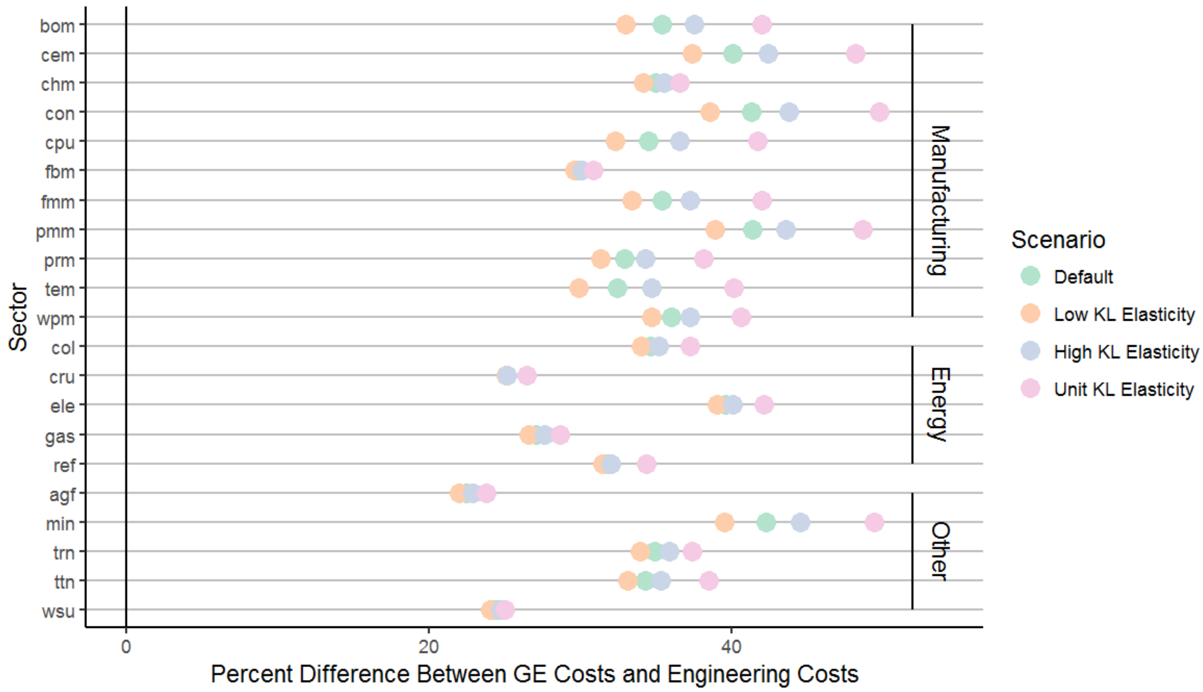

Figure 9: Sensitivity of General Equilibrium Costs to Value Added Substitution Elasticity (*se_kl*)

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 3 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.

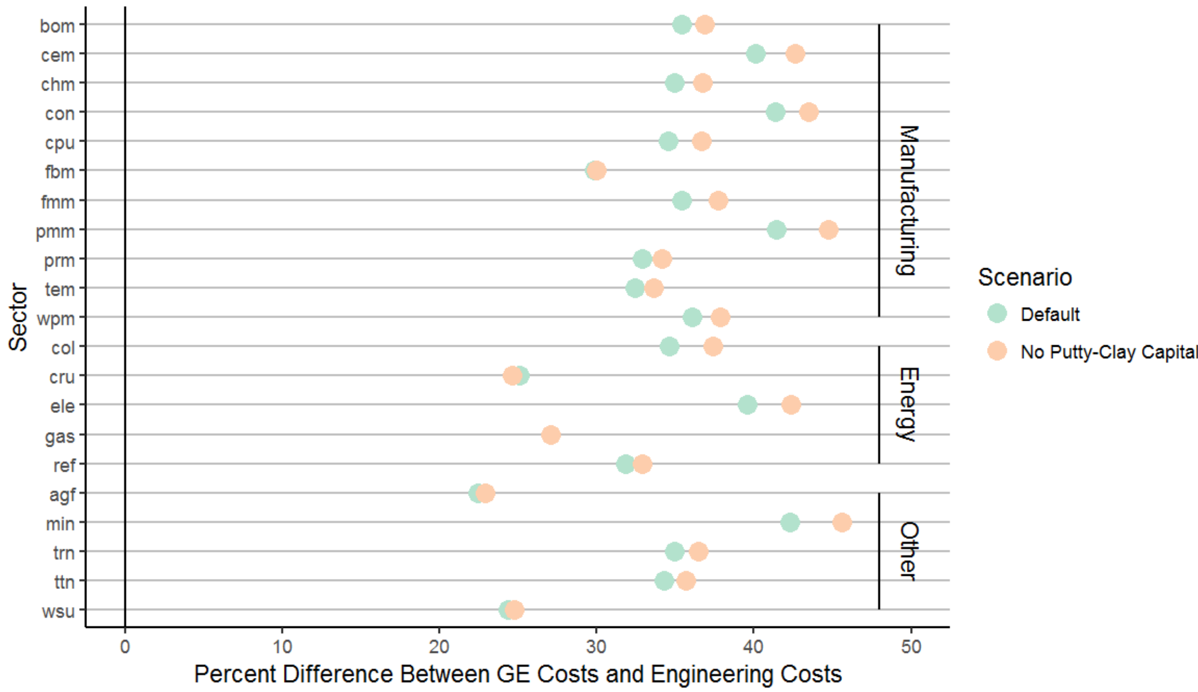

Figure 10: Sensitivity of General Equilibrium Costs to Capital Mobility

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.[23]

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

[23] 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).

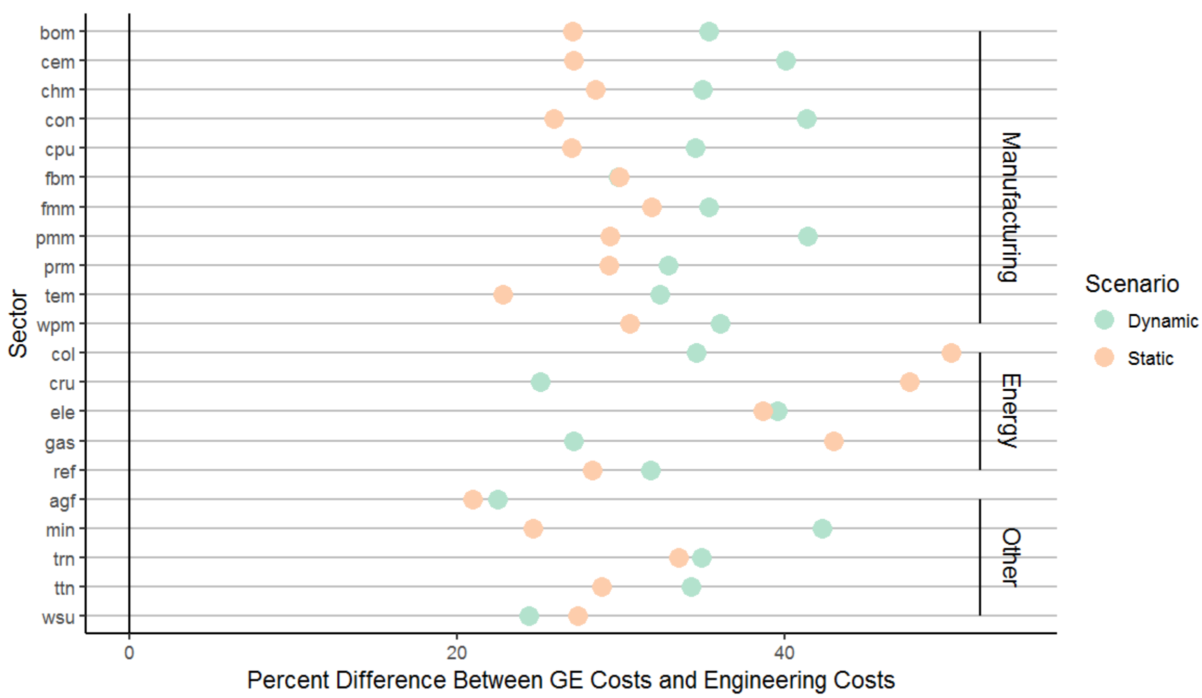

Figure 11: Sensitivity of General Equilibrium Costs to Temporal Specification

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.[24] 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. 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.

In spite of 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, by itself, the size of a regulation is not a good indicator of the relative value of a GE analysis. Second, when the benefits-cost ratio based on engineering costs is relatively close to one or 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 benefit-cost ratio. Third, if multiple regulatory options are being considered and

[24] 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

they differ significantly in their input composition, capturing the tax interaction effect via GE analysis may be of first order importance for understanding their relative welfare implications, at least from a social cost perspective. 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.

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.[25] 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).[26] We adopt the substitution elasticities in the intra-temporal utility function's energy bundle

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

[26] 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 Goulder and Hafstead (2018). 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	--