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The Importance of Source-Side Effects for the Incidence of Single Sector Technology Mandates and Vintage Differentiated Regulation

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Alex Marten[1,2]

Abstract

Understanding the distribution of regulatory costs is key to evaluating whether a rulemaking exacerbates or ameliorates preexisting economic disparities and is of stated interest to many stakeholders and policy makers. Previous studies on the incidence of command-and-control environmental regulations have predominantly focused on the distribution of costs through final goods prices (the use side). However, the impact of regulations on household income (the source side) can be of first-order importance in determining the overall incidence. Using a detailed computable general equilibrium model of the U.S. economy we study the incidence of single-sector technology mandates across a broad set of industrial sectors. We find the use-side incidence is notably regressive but the source-side effects are progressive on average and tend to dominate the overall incidence of costs. This occurs as a significant share of regulatory costs is passed on through lower returns to capital and natural resources, which predominantly affects upper-income households, while indexed transfer payments partially shields the purchasing power of low-income households from increases in output prices. However, when the regulated sector predominantly produces final goods with inelastic demand and low trade exposure (e.g., utility services) we find that the use-side incidence can dominate leading to regressive distribution of regulatory costs. Finally, we find that the common practice of vintage differentiation, whereby only new sources of pollution are covered, can cause a significantly more regressive distribution of costs, all else equal.

Keywords: environmental regulation, incidence, general equilibrium

JEL Classification: Q52, C68

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[2] 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.

1 Introduction

The costs and benefits of environmental regulation are not expected to be felt uniformly across the population. Understanding the distribution of these impacts is important for determining whether a rulemaking exacerbates or ameliorates preexisting disparities. In recent years, there has been a push to provide decision makers and the public with better information as to the distribution of benefits from reducing pollution exposure across income groups.[3] However, assessments of how the costs are distributed across income groups remain absent from federal analyses of environmental regulations in the United States (Robinson et al., 2016).[4]

The economic incidence of regulation has two primary components: the "source side" associated with changes in the payments to primary factors of production (capital, labor, land, natural resources) and thus the sources of income; and the "use side" associated with increases in final good prices which affect the use of income. In a partial equilibrium setting and under perfect competition, the share of costs borne by consumers versus factors of production will depend upon the relative elasticities of supply and demand. If demand is more inelastic than supply, then consumers will absorb a greater share of the costs than the factors of production. Under the assumption that supply is perfectly elastic in the long-run, all regulatory costs will be passed on to consumers in the form of higher prices. Based on this assumption many early studies on the distribution of regulatory costs focused exclusively on the use side (e.g., Gianessi et al., 1979; Robison, 1985; and Casler and Rafiqui, 1993). When focusing on the use side, environmental policies that affect goods which are a larger share of the budget for low income households than for high income households, such as energy, appear regressive (e.g., Burtraw et al., 2010; Hasset et al., 2009).

However, the source side can have an important role in determining both the short-run and long-run incidence of regulatory costs (Fullerton and Heutel, 2007, 2010). Limited mobility of workers or capital across space and sectors will cause those factors to bear some of the regulatory costs (Fullerton and Muehlegger, 2019). Similarly, the presence of fixed factors, such as land and natural resources, will lead to non-homothetic production where the fixed factors bear some of the regulatory costs (Bento and Jacobsen, 2007). Imperfect substitution between imports and exports can also cause a share of the

[3] For example, Executive Order 12898 on Federal Action to Address Environmental Justice in Minority Populations and Low-Income Populations requires federal agencies to identify "disproportionately high and adverse human health or environmental effects of their actions on minority and low-income populations."

[4] Some regulatory analyses, such as the 2010 Portland cement National Emissions Standards for Hazardous Air Pollutants (NESHAP) consider how costs are split between consumer and producer surplus, but they do not consider how that affects the overall distribution across households. https://www.regulations.gov/document?D=EPA-HQ-OAR-2002-0051-2042

regulatory burden to fall on owners of capital (Gravelle and Smetters, 2006). Finally, behavioral response affecting investment can impact the burden borne by owners of capital (Gravelle and Smetters, 2006). Accounting for the source-side effects typically makes the distribution of regulatory costs appear less regressive. First, returns to capital make up a greater proportion of overall income for high income households and therefore, when capital bears some of the regulatory costs the distribution tends to be more progressive (Rausch et al., 2010). Second, transfer payments fund a significant share of low income households' consumption leaving them less exposed to costs distributed through the source side. The common practice of, implicitly or explicitly, indexing transfer payments to inflation can add to the progressivity of the source-side distribution (Fullerton et al., 2011, Cronin et al., 2017). Together, these effects can cause costs passed through the source side to be progressively distributed, whereby costs as a share of income are larger for higher income households (Fullerton et al., 2011; Blonz et al., 2012).

Several studies have used a general equilibrium (GE) framework to capture both the use and source-side effects for market-based policies targeting carbon pollution from fossil-fuel combustion. When the source side is considered in conjunction with the use side, the distribution of costs for first-best environmental policies may be modestly progressive, even prior to redistributing potential revenue from emissions taxes or auctioned allowances (Rausch et al., 2011). In other words, even for energy goods, where the use side is notably regressive, the progressive distribution of costs on the source side may be strong enough to dominate the overall incidence. However, for such market-based policies the complete design, including how revenue is recycled (e.g., Caron et al., 2018; Rausch et al., 2010; Rausch et al., 2011), or if it is even raised in the first place (e.g., Dinan and Rogers, 2002; Rose and Oladosu, 2002; and Parry, 2004), is critical for determining the overall incidence. Second best policy designs, such as renewable energy standards or cap-and-trade with incomplete coverage, may have cost distributions that are dominated by the use-side effects and therefore, remain regressive even when accounting for the source side (Rausch and Mowers, 2014).

Research on the overall cost incidence of environmental policies (i.e., use and source-side effects) has predominately focused on the distributional impacts of market-based policies, often with economy-wide coverage. However, in practice market-based policies are rare and command-and-control policies, usually affecting only a single sector, are the most common. The scant attention given to the incidence of command-and-control regulations has been primarily focused only on the use side.[5] Fullerton and Heutel

[5] Fullerton (2008, 2011), Bento (2013), and Robinson et al. (2016) provide excellent reviews of the previous literature on the incidence of environmental regulations.

(2010) use a stylized two-sector static GE model to demonstrate that source-side effects are also important for determining the distribution of costs for command-and-control environmental policies, such as performance standards and technology mandates. However, the strength of the source-side effect for sector-specific technology mandates remains an open question, including its sensitivity to the affected sector and the input composition of the abatement technology. Such information is critical for interpreting the results of prior use-side studies of command-and-control regulations and for determining the appropriate scope of future distributional analyses.

We use a detailed computable general equilibrium (CGE) model of the U.S. economy to study the incidence of regulatory costs from single sector technology mandates and evaluate the strength of the source-side effects in defining the distribution of costs. The application of a CGE framework allows us to capture both the use and source-side effects of environmental regulations in a consistent manner. The use of a CGE model also allows us to capture many of the conditions previously found to be important for estimating source-side effects, including limited sectoral and spatial mobility of capital, fixed factors in production, imperfect substitution between imports and exports, and indexed transfer payments. Similar to previous studies, we find that the use-side incidence of technology mandates is notably regressive. However, we find that the source-side effects are progressive on average and, in the scenarios we study, dominate the overall incidence of costs from environmental regulations. We find that this result is robust across the sector subjected to the regulation and the composition of inputs required by the abatement process.

In addition, we examine the distributional implications of vintage differentiation, which is a common feature of environmental regulations that can have important source-side effects. The practice of exempting or setting less stringent standards for existing sources, relative to new facilities, has the effect of generating scarcity rents that may be captured by the un- or less-regulated firms (Fullerton and Metcalf, 2001). The distribution of scarcity rents to owners of existing capital can result in a more regressive source-side distribution of costs.[6] Parry (2004) shows that even when the regulated goods represent a small share of low income households' total consumption, policy designs, such as grandfathered permits, that transfer scarcity rents to high income households can be highly regressive. For the case of technology mandates,

[6] For example, in 1973 the U.S. Supreme Court decision in favor of the prevention of significant deterioration under the National Ambient Air Quality Standards imposed potential entry costs on new firms even in attainment areas. Despite the implied increase in regulatory stringency the ruling resulted in an increase in asset prices for regulated firms with existing facilities signaling an increase in the value of existing capital due to the increased market entry costs (Maloney and McCormick, 1982).

we compare the case where all sources of production are affected to the case where only new sources are regulated. We find that increased returns to owners of existing capital under vintage differentiated regulations, can lead the incidence of costs to be significantly more regressive on average compared to the case where all production sources face similar abatement costs.

The remainder of the paper is organized as follows. Section 2 presents details of the CGE models used, along with the stylized regulations studied and the approach to quantitatively measuring the average progressivity of regulatory costs. Section 3 presents the results of our regulatory simulations and Section 4 provides discussion.

2 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 during a 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). As such, a CGE model is able to capture the distribution of regulatory costs on both the use and source side in an integrated framework. Section 2.1 describes the CGE model we use to examine the cost incidence of regulation. Section 2.2 describes how we model command-and-control environmental regulations and Section 2.3 introduces the approach we use to quantitatively measure the average progressivity of the cost distribution.

2.1 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.[7,8] 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,

[7] We use a recursive naming convention, where SAGE stands for SAGE is an Applied General Equilibrium (SAGE) model.

[8] In practice, the capital stock is not fixed and the behavioral response of savers to the regulation can affect the share of the burden borne by capital owners making an intertemporal model important for assessing the source side incidence (Gravelle and Smetters, 2006).

2014). In this section, we provide a general description of the version of the SAGE model used in this paper. Marten and Garbaccio (2018) provide detailed technical documentation of the model.

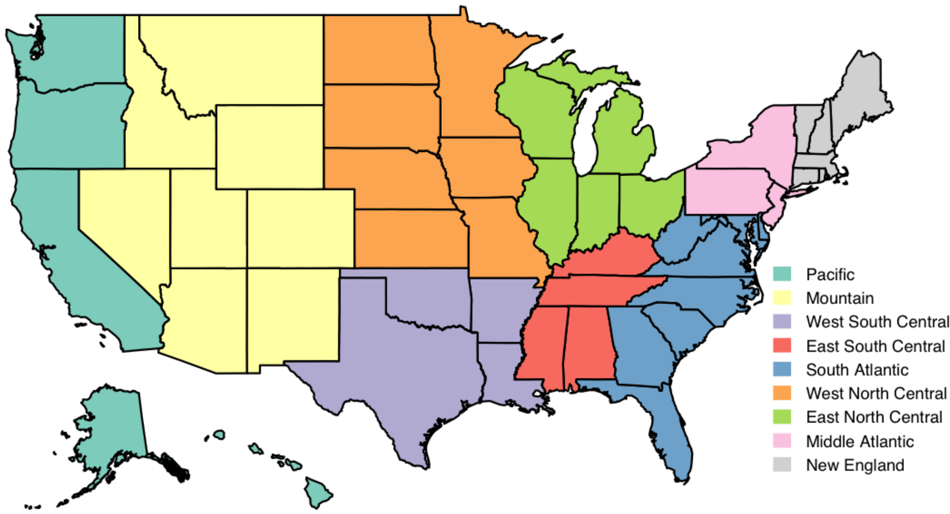


Figure 1: SAGE Regions

The model represents the nine Census regions of the United States (Figure 1). Labor is assumed to be immobile across regions, as is capital once it is installed; however, savings is mobile across regions. Trade in goods 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).

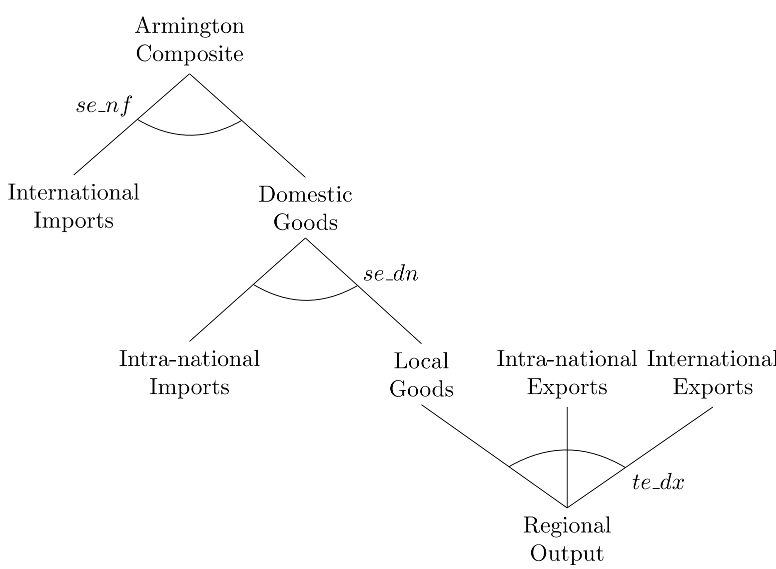


Figure 2: Armington Trade Specification

On the demand side, the first decision in defining the Armington composite is between consuming locally produced goods and those imported from other regions within the United States (center-left of Figure 2). 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 (top-left of Figure 2). Similarly, on the supply side regional output can be consumed locally, exported intra-nationally, or exported internationally (bottom-right of Figure 2). 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 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	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.

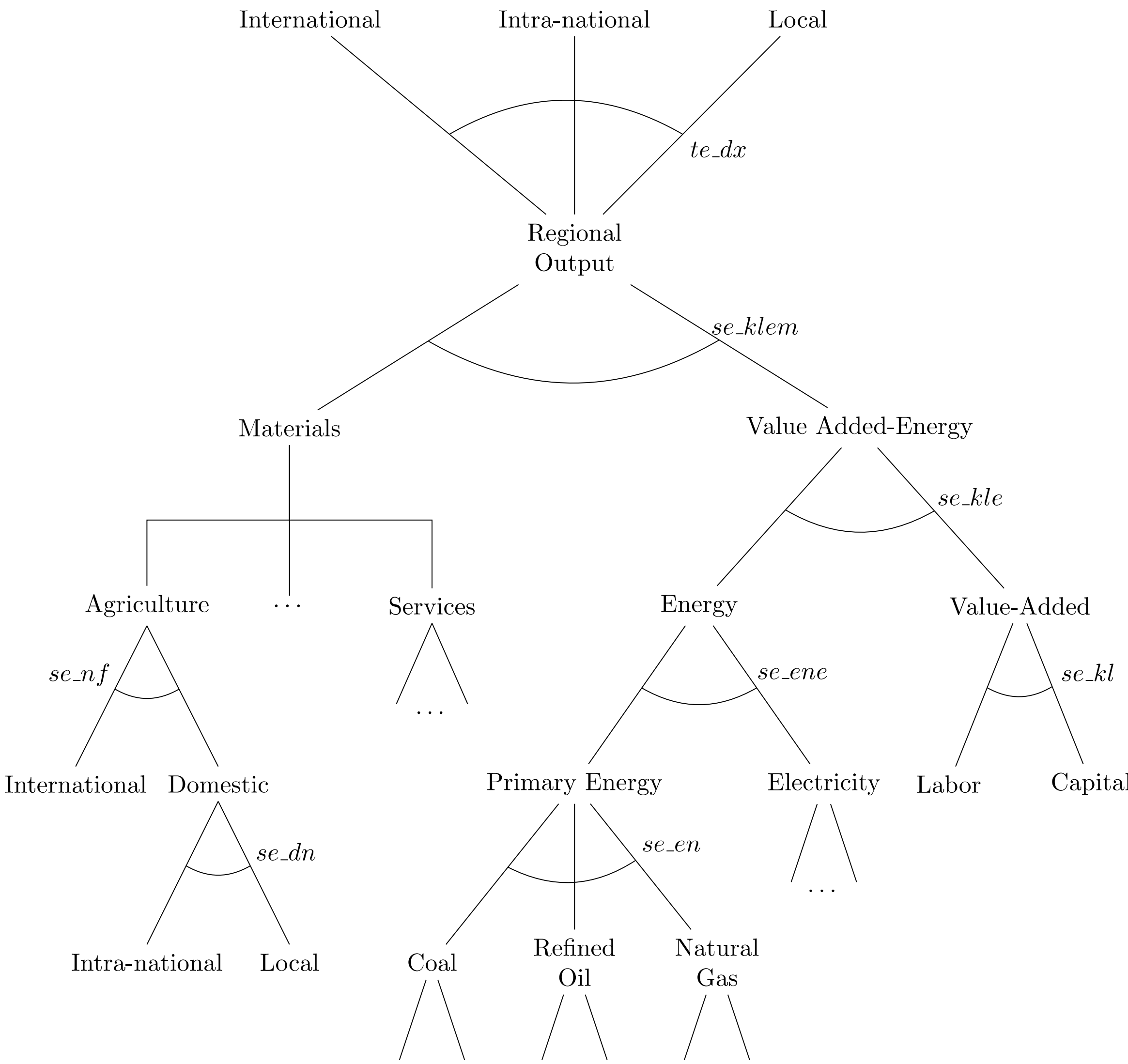


Figure 3: General Production Structure

Within each region, SAGE also models five representative households based on their pre-tax money income level in the initial year of the model (Table 2).[9] 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).[10]

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 partial 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 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

[9] Note that money income includes cash based transfer payments, such as Social Security and the Supplemental Nutrition Assistance Program, but does not include non-cash based transfer payments, such as Medicare and Medicaid, which are included in consumption.

[10] Households are differentiated based on income sources and consumption expenditures. However, the substitution elasticities within the households' utility functions are consistent across the representative households.

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.

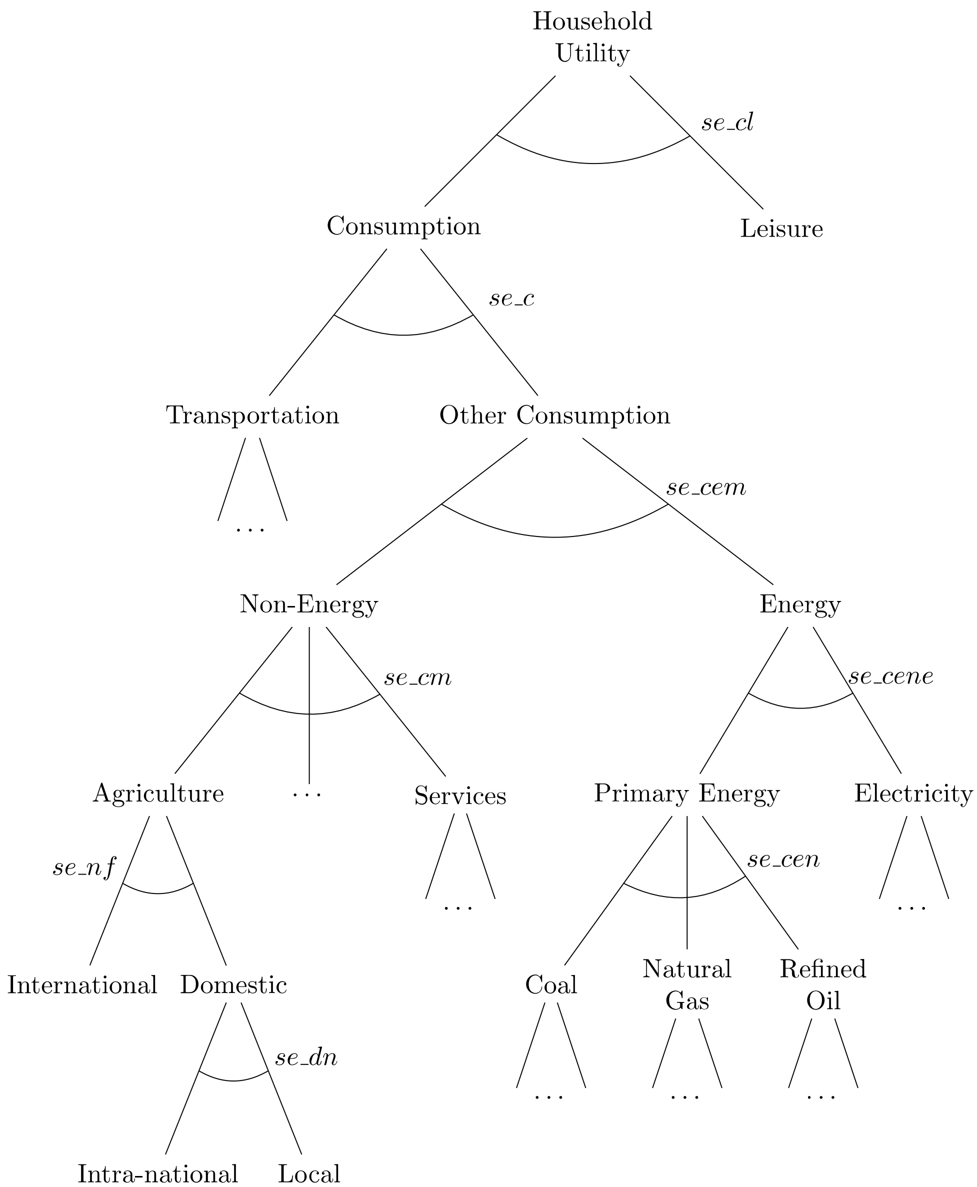


Figure 4: Household Preferences

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.

In this paper, we extend the model of Marten and Garbaccio (2018) to account for changes in marginal and average tax rates across households with different incomes. The SAGE model matches observations of final good consumption, factor income, and personal taxes across households by using transfers from the government to balance the household budget constraints in the benchmark social accounting matrix. The transfer payments are indexed to the consumer price index (CPI) in the model, as is common in practice (Fullerton et al., 2011). However, in the model developed by Marten and Garbaccio (2018) all households in a region face the same effective marginal personal income tax rate for capital and labor income. This means that government transfers to households include a recycling of tax revenue to make up the difference between the value of personal income taxes collected at the marginal rate compared to average rate. This is of concern for measuring incidence since a portion of household income that would be valued with factor prices in reality, are instead being valued at final good prices (i.e., the CPI) in the model. Therefore, we extend the model to better represent average personal income tax rates to improve the model's representation of the share of household income due to transfers, while also improving the representation of effective marginal tax rates across households.

In the model, we represent effective marginal personal income tax rates separately for capital and labor income to better capture the average marginal taxes paid on an additional dollar of wage income versus investment income for the population underlying the representative household. We also model separate effective Federal Insurance Contribution Act (FICA) marginal tax rates by household to capture the contribution limit on old age survivor insurance that reduces the marginal FICA tax rate for higher income households. We estimate region and income specific earnings weighted average effective marginal tax rates using the National Bureau of Economic Research's TAXSIM model (Feenberg and Coutts, 1993). We generate a representative sample of regional tax units using the U.S. Census Bureau's Current Population Survey (CPS) March Supplement and compute marginal FICA and labor income tax rates based on perturbing wage income. To compute the regional effective marginal tax rates used in the model we take a weighted average based on wage income and the CPS March Supplement person weights. To compute the marginal tax rate on capital income we perturb long-term capital gains income and take a weighted average based on investment income and the CPS March Supplement person weights. A detailed description of the methodology is presented in Appendix B.

To match the observed average tax rate in the IMPLAN dataset we refund the difference between taxes that would be paid according to the marginal tax rate and the observed benchmark tax payments and index these transfers at factor prices instead of the CPI used for other transfers. The price used to index this tax refund is a weighted average of factor prices with weights based on benchmark year income shares. This approach allows us to use marginal tax rates to model behavior, while ensuring that the after-tax factor income share matches the observations in the benchmark dataset. A detailed description of the methodology is presented in Appendix B.

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).[11] The MCP is solved using the PATH solver (Ferris and Munson, 2000).

2.2 Modeling Regulations

While there are some notable exceptions, environmental regulations rarely rely on market-based incentives in practice. 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 technology mandates that a sector use more inputs to produce the same amount of output. Therefore, we follow Marten et al. (2018) and focus our analysis on the additional inputs to production required for compliance.

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 activities are the same as across inputs to production activities in 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

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

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. Therefore, we consider a range of potential input requirements for compliance activities. First, we 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.[12] 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 also consider the case of a Hicks'-neutral abatement requirements, along with capital- and labor-only cases.

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 to forego the burden of the regulation). 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.[13]

2.3 Measuring the Average Progressivity of the Regulatory Cost Distribution

It is useful to have a quantitative measure of the average progressivity of the distribution of regulatory costs for at least two reasons. First, if the distribution of costs as a share of income is not everywhere either increasing or decreasing with income the distribution will not be unambiguously progressive or regressive, respectively. Second, it is useful to have a single quantitative measure that describes the

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

distribution of costs to facilitate comparisons across the regulatory scenarios studied. Therefore, we use the Suits (1977) index, which is commonly used to measure the average progressivity of taxes to facilitate comparison, and can easily be adapted to the cases of environmental regulations.[14] Consider the Lorenz curve mapping the cumulative distribution of income across households to the cumulative distribution of social costs across households, as depicted in Figure 5. The linear curve OB represents that case where the household costs are proportional to income. The convex curve OCB represents the case where the regulatory costs are progressively distributed throughout the entire distribution – costs initially increase slower than income but then increase faster than income at the top of the income distribution. The dashed line represents the case where the costs are increasing slower than income for both the low- and high-income households, but faster than income for middle-income households. In this case, which is common in our results, middle-income households bear a disproportionate share of the regulatory costs relative to the initial income distribution. For cases, such as the dashed line in Figure 5, the Suits index tests whether the distribution of costs in these cases is progressive on average.

Specifically, the Suits index measures the average progressivity as

$$S = 1 - \frac{Y}{Z} \ , \tag{1}$$

where Z is the area of the triangle OAB and Y is the area between the Lorenz curve and the axis OA. For the solid curve OCB, Y is the area OABC between the Lorenz curve and the axis. If the regulatory costs are proportional to income, $Y = Z$ and $S = 0$. If the regulatory costs are distributed progressively on average relative to income then $S > 0$ as $Y < Z$ and if the regulatory costs are distributed regressively on average relative to income then $S < 0$ as $Y > Z$.

[14] This approach is closely related to the suggestion of Robinson et al. (2016) to use Gini coefficients to quantitatively study the distribution of regulatory costs.

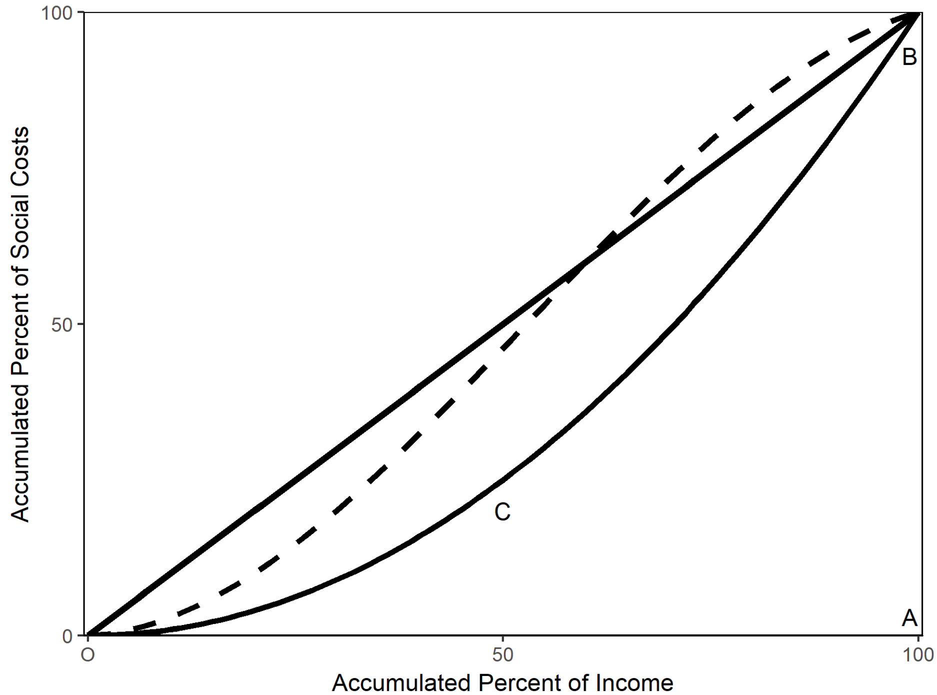


Figure 5: Lorenz Curve of Regulatory Costs

3 Results

We consider a suite of 168 illustrative regulatory scenarios, across all combinations of the twenty one regulated sectors, four input assumptions for the compliance technology (Hick's neutral, capital only, labor only, or Nestor and Pasurka shares), and two vintage differentiation assumptions (all sources and new source only). In Section 3.1 we begin by examining the share of social costs borne by each income quintile when all emission sources are affected. In Section 3.2 we consider the impact of these costs relative to income and decompose the use and source-side effects. In Section 3.3 we consider the distributional impact of vintage differentiation.

3.1 Share of Costs by Household Income

We begin by considering the distribution of social costs across income quintiles. The approximate percentage of aggregate social costs borne by each income quintile are presented in Figure 6 for the regulatory scenarios in which all sources are affected by the policy. [15] As expected the level of costs is

[15] The household definitions in Table 2 are the best approximation of income quintiles we can model due to limitations in the underlying benchmark dataset. However, the share of households in each income bin is not equal to exactly 20%. To approximate the share of costs borne by income quintiles we assume that per household costs

increasing with income. Households in the bottom income quintile are expected to bear around 3% to 8% of the overall social costs, while the top income quintile is expected to bear around 35% to 53% of the overall social costs. The distribution is relatively linear across the first four income quintiles, but overall the distribution across income quintiles is convex.

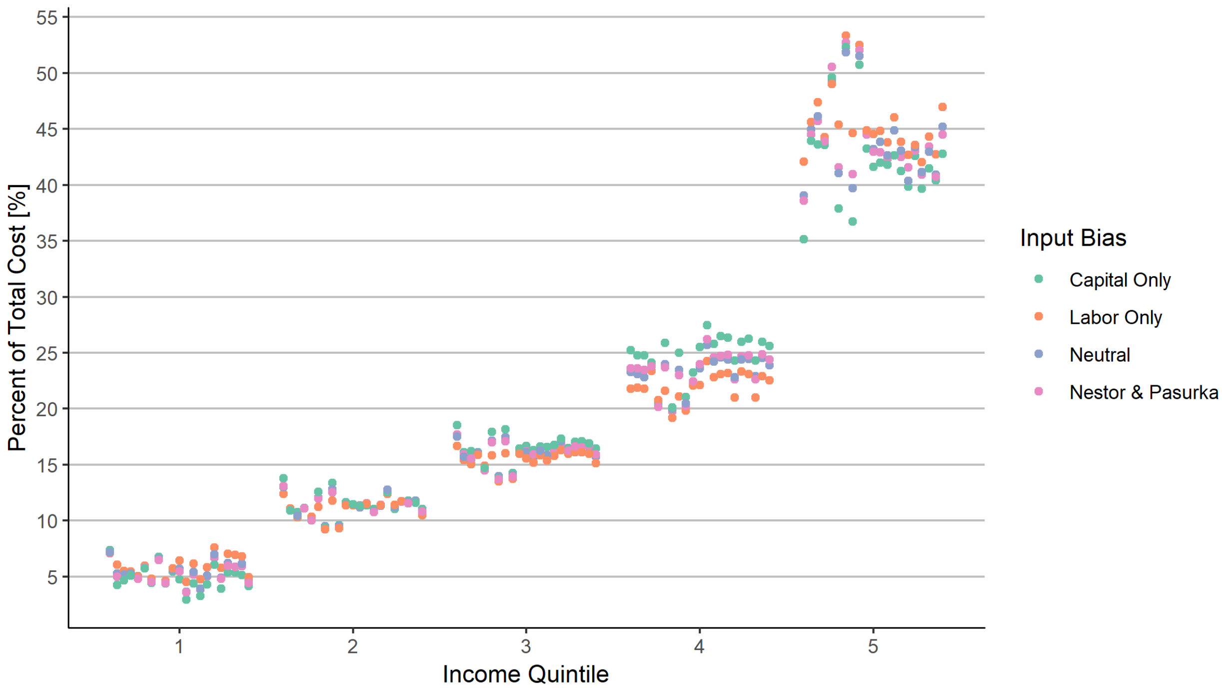


Figure 6: Approximate Percentage of Costs Borne by Income Quintiles

Note: The dispersion of the points along the x-axis within a household is only intended to improve the readability of the figure. However, the dispersion is the same for each sector, providing comparability within and across households.

Consumption increases with income and therefore, it is expected that higher income households will bear a larger share of the costs. However, these shares are substantially different from those quintiles' overall share of consumption. Under the assumption of full price pass through (i.e., no source-side effects) the share of costs borne by each quintile would be consistent with their share of consumption. However, the bottom income quintile consumes 11% of all goods and services compared to their 3% to 8% share of the regulatory costs under the illustrative scenarios. While the top income quintile consumes 31% of all goods

experienced by each of the five representative households is representative of the per household costs borne by the associated quintile and apply those estimates to the population in each quintile. The largest effect of this scaling is on the share of costs in quintiles 4 and 5, as the income bracket for hh4 covers more than 20% of the population while the income bracket for hh5 covers less than 20% of the population.

and services compared to their 35% to 53% share of the regulatory costs. If one were to instead compare the share of final goods consumption for the directly regulated to share of regulatory costs a similar pattern emerges, with the lowest quintiles share of costs below their consumption share and the highest quintiles share of costs typically above their consumption share.

The difference between households' consumption shares and their regulatory cost shares is due to the presence of source-side effects. In the near- to medium-run, production exhibits decreasing returns to scale due to rigidities on the supply side. For example, limited mobility of workers or capital across space and sectors, which are partially captured in the model through the putty-clay representation of capital and regional representation of labor markets. The upward sloping supply curves due to limited factor mobility cause a portion of the regulatory costs to be passed through returns to primary factors instead of final goods prices. Sectors, such as fossil fuel extraction and agriculture, that are reliant on fixed factors of production will also see some costs passed on through lower returns to those fixed factors, for similar reasons. Since high income households own a larger share of effective primary factor income they are more susceptible to costs from the source side. Furthermore, a notable share of consumption for households at the bottom of the distribution is funded through transfer payments, which are predominantly (over 90%) indexed for inflation (Fullerton et al., 2011). Therefore, the purchasing power for a substantial portion of those households' income is protected from increasing in final goods prices as a result of the regulation. These source-side effects cause a larger share of the costs to be borne by higher income households than would be estimated by the use side alone.

3.2 Relative Burden of Regulatory Costs

As is well known, the bottom income quintile accounts for notably less than 20% of aggregate income and the top income quintile accounts for notably more than 20% of aggregate income. Specifically, the bottom quintile receives 7% of overall income after taxes and transfers compared to 46% for the top quintile.[16] Therefore, it is important to consider the distribution of regulatory costs in context of the existing income

[16] We note that these values, based on the benchmark data in our model, are consistent recent U.S. Congressional Budget Office estimates for shares of income after transfers and federal taxes by quintile (CBO, 2018). Slight differences are because CBO only accounts for federal income taxes while our model also includes state income taxes.

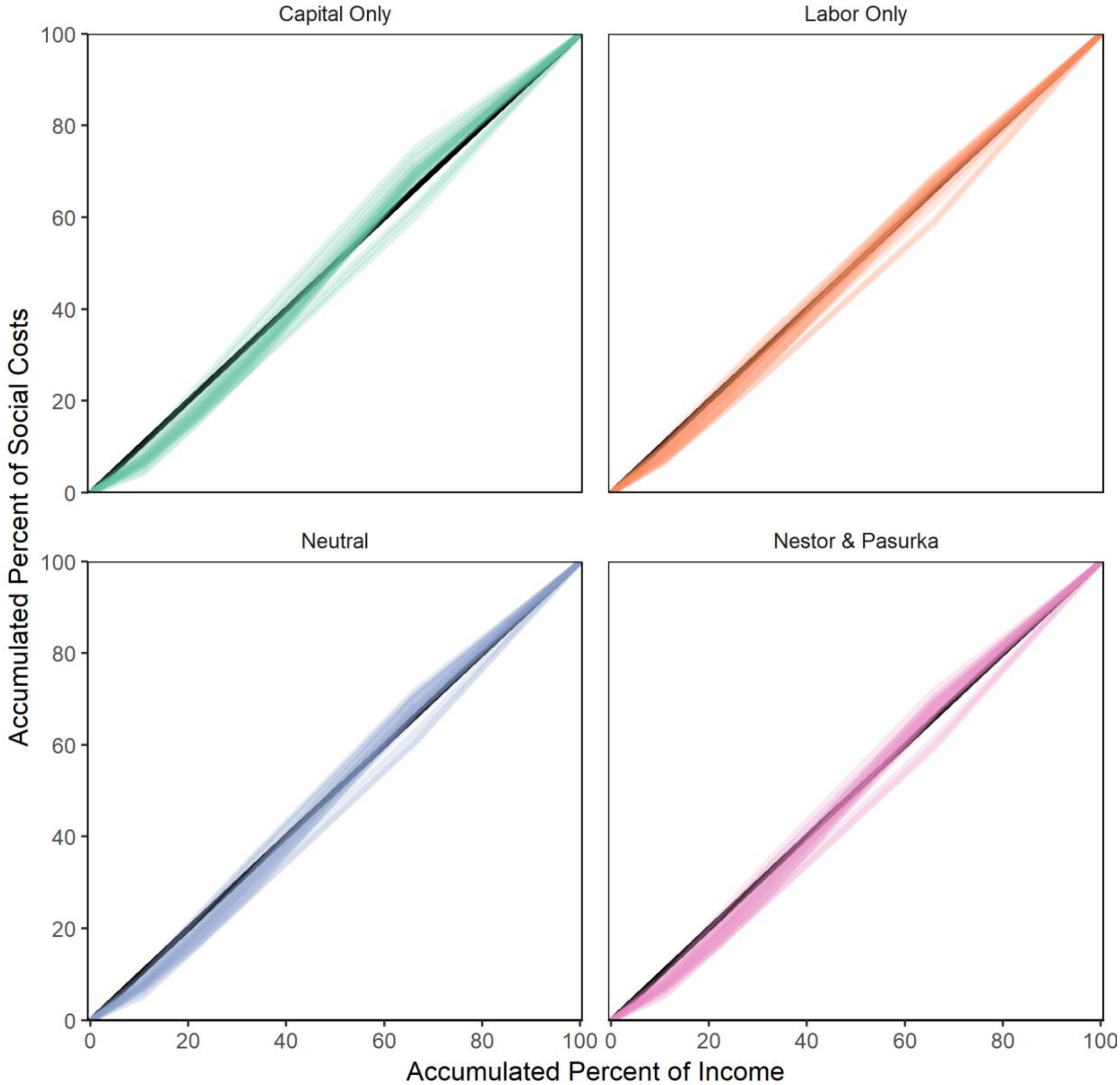


Figure 7: Lorenz Curves for Regulatory Costs

Note: Each panel represents a different assumption about the input composition of the required compliance activity. Within each panel the 21 curves represent the regulatory scenarios varying the directly regulated sector.

distribution to better understand the distribution of burden. For our set of regulatory scenarios in which all sources of pollution are covered, Figure 7 presents the Lorenz curves mapping the cumulative distribution of income after transfers and taxes to the cumulative distribution of regulatory costs. If a curve follows the 45-degree line that indicates that the costs are distributed proportionally to income. In scenarios where the curve always remains below the 45-degree line, regulatory costs as a share of income are always increasing with income. For scenarios where the curve starts below but then crosses the 45-degree line, costs as a share of income are higher for middle-income households than for low- and high-income households.

In general, the distribution of regulatory costs remains fairly close to the solid 45-degree line representing a neutral distribution (within the context of the existing income distribution). However, for most scenarios the Lorenz curve starts out below but then crosses the 45-degree line. In these cases, the regulatory costs are initially distributed progressively, but eventually costs as a share of income begin to fall as income increases. In all but one of the 84 simulations the household costs as a share of benchmark income is increasing with income for the first three quintiles. However, between the third and fourth income quintiles, costs as a share of income increase in only 71% of the simulations and in only 14% of the simulations do costs as a share of income increase between the fourth and fifth quintile. Therefore, only a small share of the illustrative regulatory scenarios have a cost distribution that is progressive throughout the entire income distribution. In most cases, the highest income quintile has costs as a share of income that are also less than the third (86%) and second (74%) income quintiles. In 11% of the simulations the highest income quintile has costs as a share of income that are lower than the lowest (first) income quintile. Therefore, while the source-side effects increase the amount of regulatory costs borne by high income households, their share of costs remains less than their share of overall income.

To more easily compare the incidence across the illustrative regulatory scenarios we turn to the average progressivity of the cost distribution, as measured by the Suits index described in Section 2.3. The Suits index for the scenarios in which all pollution sources in the regulated sector are subject to the regulation is presented in Figure 8. A positive value for the index indicates a distribution of costs that is progressive on average, with a higher index value indicating a more progressive distribution on average. A negative index value indicates that the distribution of costs under that scenario are regressive on average. In nearly all cases, the distribution of regulatory burden is slightly progressive on average, with a mean index of 0.01 and a standard deviation of 0.04.

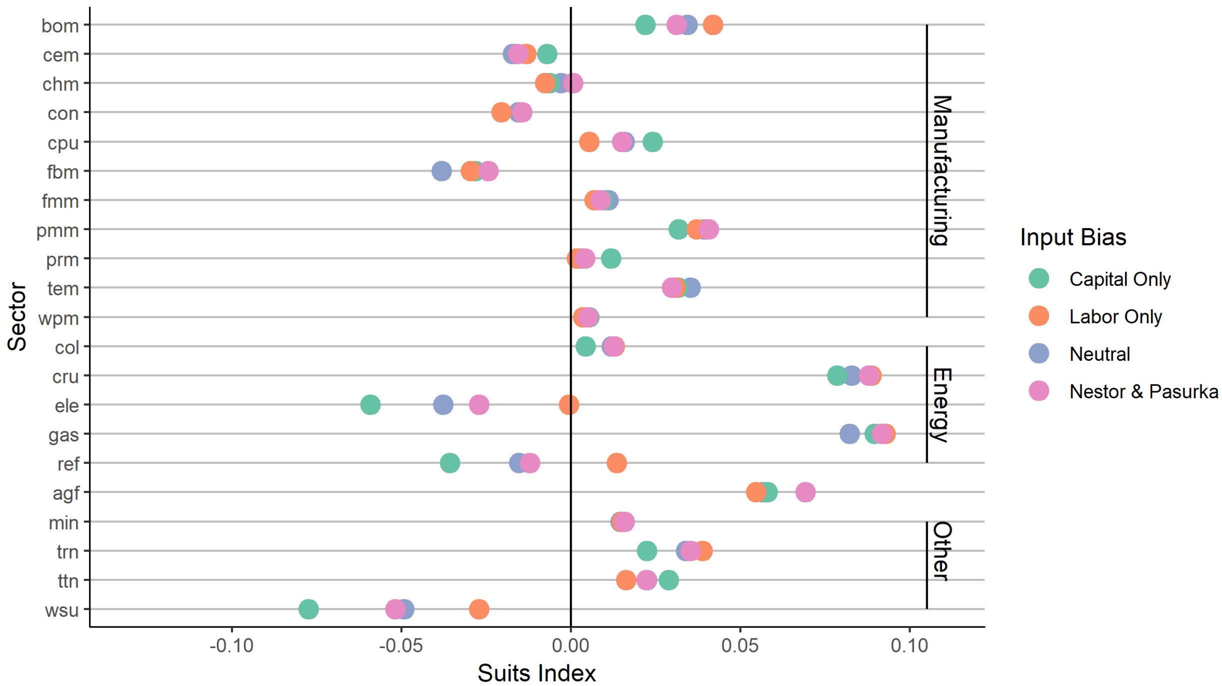


Figure 8: Suits Index

When examining the estimates of the Suits index three themes emerge. First, the distribution of regulatory costs is more sensitive to the regulated sector than the input composition of the abatement activity. Characteristics of the sector being regulated have an important influence on the strength and direction of the use-side effects and in turn the overall cost distribution. The simulations that exhibit a relatively more regressive distribution of costs are associated with sectors where a large share of output is consumed as a final good and the per capita consumption of the commodity are relatively similar across households (i.e., low elasticity of demand with respect to income). For example, water, sewage, and waste services (wsu), food and beverage manufacturing (fbm), electricity (ele), and refined petroleum (ref). For these commodities, final consumption scales less than proportionally with income leading the use-side incidence to be fairly regressive. This effect works in the opposite direction as well. Regulations affecting sectors where final good consumption is disproportionately concentrated with high income households tend to be more progressive on average. For example, while gasoline consumption rises only modestly with income leading regulations directly affecting the refined petroleum (ref) sector to be relatively regressive, the fact that new cars are disproportionately purchases by higher income households causes regulations directly affecting the transportation equipment manufacturing (tem) to have a relatively progressive distribution of costs.[17]

Second, for most sectors, the distribution of costs is relatively similar across the different input composition scenarios. The input composition affects the distribution of costs by influencing the degree to which regulatory costs are passed through different factor prices. However, as will be demonstrated in more detail in Section 3.2.1, we find that the source-side incidence is dominated by the role of the existing capital stock. When all sources of pollution are affected an important avenue through which regulatory costs are distributed is the returns to existing capital in the regulated sector. Due to its limited mobility, regulations that lower the productivity of existing capital lead the owners of that capital stock to bear a notable share of the incidence. This effect tends to dominate the source-side distribution of regulatory costs leading the input composition of compliance to have a small effect. Exceptions are regulations in sectors producing water, sewage, and waste services (wsu), electricity (ele), and refined petroleum (ref) where the input composition of abatement can have a notable effect on the distribution of costs. In these sectors, a significant share of output is associated with final good consumption, demand is relatively inelastic, and foreign imports are small. In these situations, the owners of existing capital remain able to pass on a significant share of the regulatory costs to consumers, such that impacts on the return to existing capital are no longer the dominant effect on the source side.

Third, regulations that fall on sectors associated with sector-specific fixed factors (i.e., natural resources or land) are more progressive in general, particularly regulations in the natural gas extraction (gas), crude oil extraction (cru), and agriculture and forestry (agf) sectors. While all production exhibits decreasing returns to scale in the short- to medium-run due to the limited adaptability of the existing capital stock, in most sectors it is assumed to approach constant returns to scale in the long-run. However, sectors associated with a sector-specific fixed factor continue to exhibit decreasing returns to scale. Therefore, some of the regulatory costs will continue to be passed through in the form of lower returns on the fixed factor, leading to more progressive and impactful source-side effects from regulations in these sectors. The few Lorenz curves in Figure 7 that remain below the 45-degree line for the entire income distribution are cases where the regulated sector is associated with a sector-specific fixed factor.

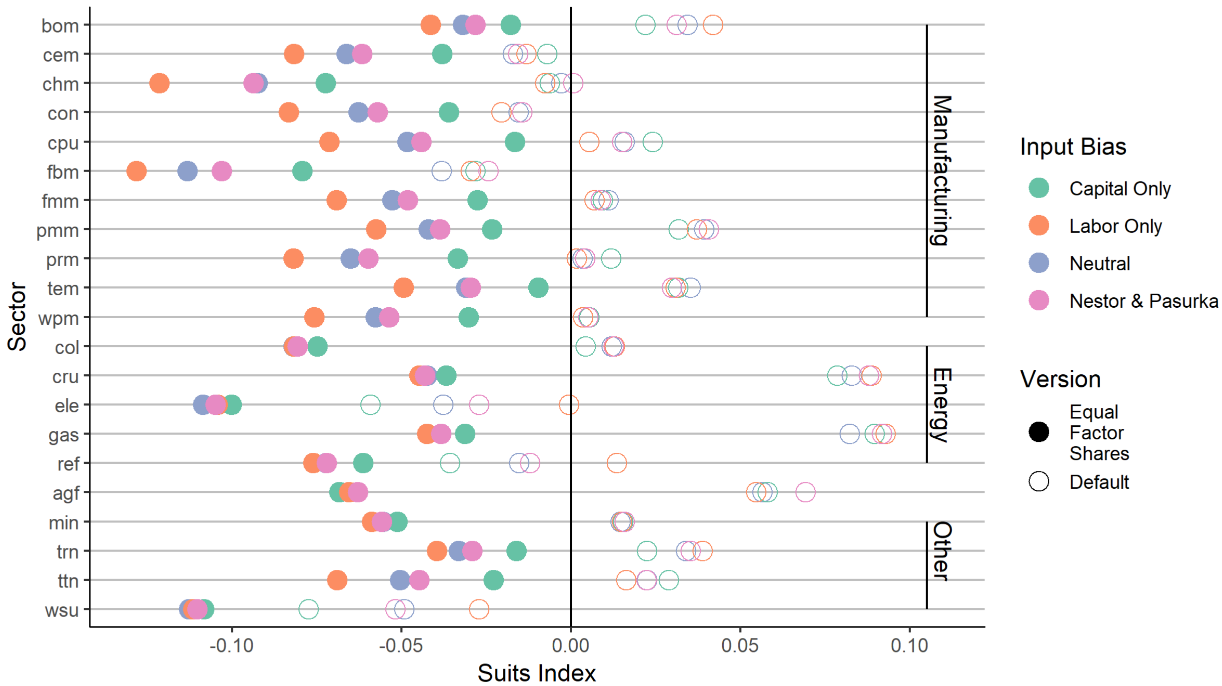
[17] It is important to note our model does not include a detailed representation of the used car market, which can be important for evaluating the incidence of regulations affecting the production of automobiles (Jacobsen, 2013).

3.2.1 Use- and Source-Side Incidence

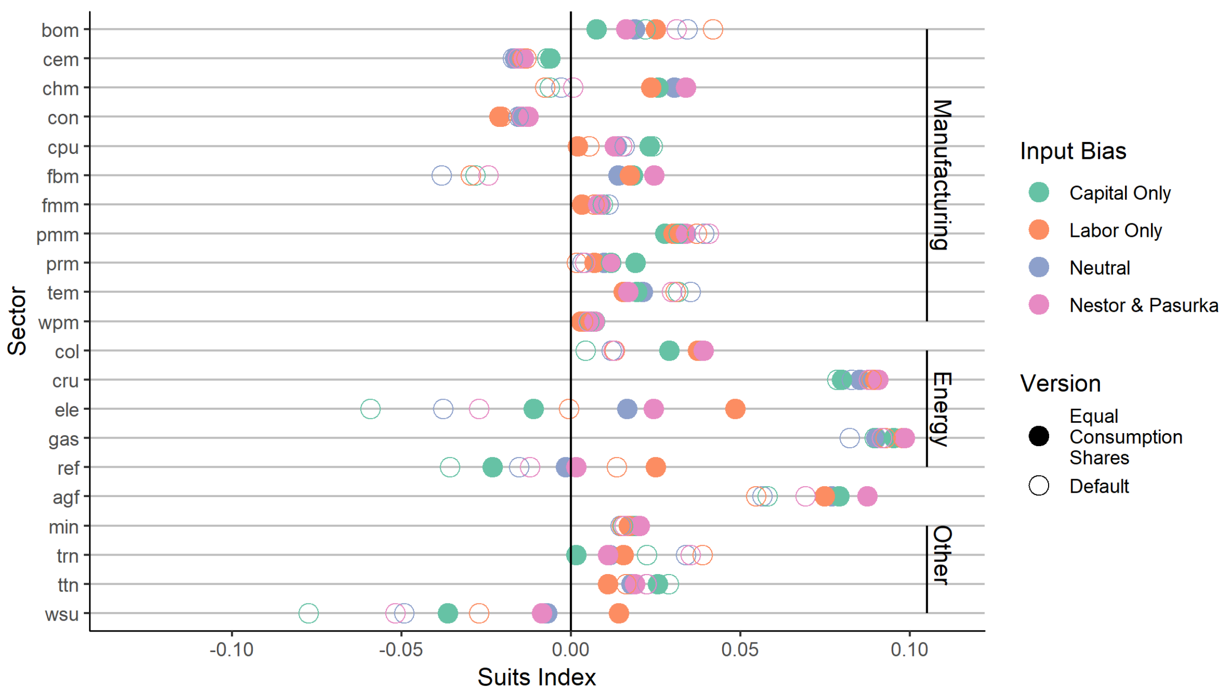
To better understand the role of the use and source side in determining the distribution of costs we conduct two decomposition runs, similar to the approach of Rausch et al. (2011). To estimate the distribution of costs through the use side we recalibrate the model so that the after-tax shares of income from capital, labor, and resources are equal across households.[18] When the income source shares are recalibrated to be equivalent across households the distribution of costs will be determined by differences in consumption shares, thereby identifying the incidence of the use side. To estimate the distribution of costs through the source side we recalibrate the model so that the consumption shares are equal across households.[19] When the consumption shares are equal the distribution of costs relative to income will be primarily determined by differences in income sources, thereby identifying the incidence on the source side. Figure 9 presents the Suits index estimates for the two recalibrations. For ease of comparison the hollow points represent the Suits index estimate from the default model, as presented in Figure 8.

Figure 9a is based on the recalibration in which after-tax factor income shares are set equal across households, thereby highlighting the distribution of costs through the use side. As expected, the distribution of costs on the use side is notably regressive. This result is more pronounced for scenarios where the per capita consumption of the regulated sector's product is similar across households (e.g., water, sewer, and waste services (wsu) and electricity (ele)). Some of the costs are still passed on to factors of production through the source side, but those costs will be proportional to income under the recalibration. Therefore, the differentiation in the Suits index across input composition scenarios is indicative of the impact that assumption has on the share of costs estimated to be passed through the source side. Within a given sector's results, a Suits index closer to zero suggests a greater share of the costs are passed through the source side for that input composition. For a capital-intensive abatement technology, a greater share of the cost is distributed through the source side than for a labor-intensive abatement technology, as indicated by the Suits index generally being closer to zero for capital intensive technologies in Figure 9a. This is because of the increased mobility of labor relative to capital (which is inclusive of extant capital).

[18] The shares are recalibrated to be equal across households within a region, leaving some small variation in shares across regions. Recalibrating shares to be equal across regions would require adjusting regional trade and production patterns, which would complicate the interpretation of the results.
[19] Ibid.



(a) Equal After-Tax Factor Shares



(b) Equal Consumption Shares

Figure 9: Use and Source-side Suits Index

Figure 9b is based on the recalibration in which consumption shares are set equal across households, thereby highlighting the distribution of costs through the source side. As expected, the distribution of costs on the source side is more progressive than the use side, independent of the scenario. Across the regulatory scenarios, the source-side Suits index estimates are roughly consistent with the estimates from the default calibration presented in Figure 8. These results suggest that regulatory costs are largely passed through to factor prices such that incidence estimates based on the assumption of full output-price pass through will be significantly biased, even for sectors with high levels of final good consumption that is shared almost equally across the income distribution. There are multiple reasons that source-side effects will be important, including limited sectoral and spatial mobility of capital, fixed factors in production, imperfect substitution between imports and exports, and indexed transfer payments.

The results of this decomposition also provide insight into the importance of the input composition of compliance and the immobility of extant capital on the distribution of regulatory costs. As seen in Figure 9a, the share of costs passed on to consumers through the use side is relatively sensitive to the input composition of compliance. However, the source-side distribution in Figure 9b is not notably affected by the input composition. This suggests that while the input composition's effect on the share of costs passed through output prices is large relative to the overall use-side effect, it is small relative to the source-side effect, in most cases. This is because the source-side incidence is driven in large part by the role of extant capital. The limited mobility of extant capital causes a majority of the source-side incidence to be passed through lower returns to existing capital. Under the extreme assumption that extant capital is fully malleable, the input composition has a greater effect on the overall incidence, however the source-side effects still dominate the overall incidence (see Appendix D). Therefore, while the low mobility of extant capital is a strong force in defining the incidence of regulatory costs in our central results, without this assumption other source-side drivers remain stronger than those on the use side.

We note that in a few cases, the estimates of the Suits index under the case of equal consumption shares are lower than the default estimates. This occurs for sectors where high income households have a notably larger share of final good consumption for the sector (e.g., balance of manufacturing (bom), transportation equipment manufacturing (tem), and transportation (trn), where the later includes air travel). This is because recalibrating the consumption shares to be equal alters the incidence of policy induced changes to transfer payments, which biases estimates of source-side Suits index downwards. In the model, the consumer price index (CPI) used to index transfer payments is defined as the post-tax consumption weighted national price index in the benchmark year. This is similar to the general approach used by the U.S. Bureau of Labor Statistics to create the U.S. CPI that is used to index many transfer payments in practice.[20] When a regulation is imposed on a sector where high income households have a disproportionately high share of final consumption, the CPI will increase more than the unit price of consumption for lower income households. As a result, under some regulatory scenarios the change in transfer payments to low income households may more than compensate for any price changes they face in the default model. When the model is recalibrated to set the consumption shares equal across households such an outcome is no longer possible. Therefore, in the cases where higher income households disproportionately consume the directly regulated sector's product the recalibrated model with equal consumption shares will underestimate the average progressivity of the cost distribution on the source side.

3.3 Vintage Differentiation and Cost Incidence

It is not uncommon for compliance obligations under environmental regulations to be differentiated by the vintage of the affected source. One of the most common cases is that of new source standards, where the regulation only applies to sources constructed after the regulation is promulgated (sometimes referred to as the grandfathering of existing sources).[21] Therefore, we consider the sensitivity of cost distribution to vintage differentiation of the standards. We re-run all of the illustrative regulatory scenarios varying the regulated sector and the input composition of the compliance activities but only apply the regulation to production associated with new capital to approximate a new source standard. The per unit output cost of the regulation is held constant at the level used in the prior experiments, but only production associated with new capital is subject to the productivity shock associated with the regulation. The Suits index values for the vintage differentiated regulations is presented in Figure 10. Note that we do not plot results for the resource extraction sectors (col, cru, gas, min) and the agriculture and forestry sector (agf) because the model does not differentiate between new and extant capital in those sectors, as discussed in Section 2.1.

[20] In practice, over time the BLS updates the basket of goods used to calculate the U.S. CPI though it always lags changes in consumption patterns by a couple of years. If there is any substitution across consumption goods due to a regulation this will be picked up through changes in the U.S. CPI.
[21] In some cases, such as New Source Performance Standards promulgated under Section 111(b) of the Clean Air Act new sources are defined as those constructed after the regulation is proposed instead of the final promulgation date.

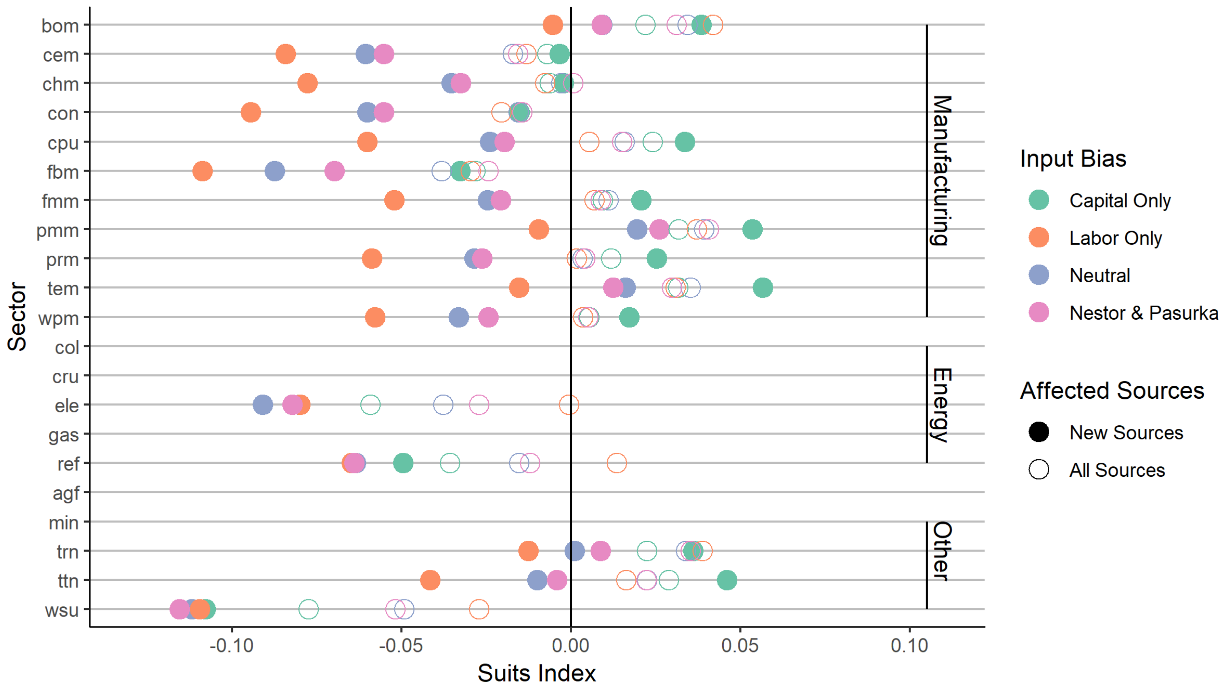


Figure 10: Suits Index for New Source Regulations

Under the new source regulations, the estimates of the Suits index are generally lower than the case where all sources face the same compliance costs, signaling that the distribution of costs for technology mandates is generally more regressive for vintage differentiated regulations. When the productivity of new sources falls, less new capital is deployed in the regulated sector and the real returns paid to existing capital see upward pressure. This represents scarcity rents being created by the regulatory design and captured by the owners of existing capital. Since returns on capital represent a significant portion of income for the top quintiles, these scarcity rents mitigate some of the regulatory impact for high income households resulting in a more regressive distribution of costs. In Appendix E, we replicate the use and source-side decomposition of Section 3.2.1 for the case of the new source regulations. Both the use and source-side distributions are more regressive for new source regulations than for the case where all sources are regulated. This highlights how vintage differentiation increases the regulatory burden passed through output prices and lowers the burden on owners of capital.

An exception are capital intensive abatement technologies, where in many cases, a new source standard has a more progressive distribution of costs than under a regulation affecting all sources. The new source regulations lower the real returns paid to new capital, relative to the baseline, due to the increased production costs imposed by the regulation. This effect on the average returns paid to new capital is most pronounced for regulations that are capital intensive, since the average marginal product of new capital is most effected under this scenario. In many of these cases, this decreases in the returns to new capital dominate any scarcity rents captured by the owners of the existing capital stock leading to a more progressive distribution of regulatory costs on average under a new source only standard. However, for most of the scenarios in which abatement is not capital intensive, any reductions in the average returns to new capital are dominated by the increased returns on the fixed existing capital stock. In sectors where demand for domestically produced goods is highly inelastic (e.g., food and beverage manufacturing (fbm), refined petroleum (ref), electricity (ele), and water, sewer, and waste (wsu)) there is ample opportunity to pass abatement costs on through prices, leading to small source-side effects. In these cases, new source regulations have a more regressive distribution of costs, even for capital intensive technologies.

For similar reasons, labor-intensive new source standards have a larger impact on the average returns paid to labor. Therefore, under these scenarios, relative to the other scenarios, a larger share of the source-side costs are passed through to labor, which is a relatively greater source of income for lower income households. Combined with the scarcity rents generated by the owners of existing capital, this causes the Suits index to be substantially lower under labor intensive new source standards than for the case where all sources are affected by the regulation. Suggesting that the distribution of costs may be significantly more regressive for a labor intensive new source standard than an equivalent sector-wide standard, all else equal.

4 Discussion

We consider the general distribution of social costs for single-sector command-and-control environmental regulations. We evaluate the incidence of costs for a suite of illustrative regulatory scenarios that vary across the affected sector, compliance input requirements, and affected vintage of sources. We find that for sector specific environmental regulations with relatively uniform effects across sources in a sector, the costs generally increase with income independent of the regulated sector or input requirements for compliance. In our regulatory scenarios, we found the share of social costs borne by low income households to be less than their share of aggregate consumption and the share of social costs borne by high income households to be greater than their share of aggregate consumption. Household costs are not proportional to consumption because not all regulatory costs are passed on through final output prices. This finding highlights the importance of accounting for source-side effects when evaluating the distribution of regulatory costs for command-and-control policies in practice.

The growth of regulatory costs when moving up the income distribution is estimated to be faster than income growth over the first four quintiles in most of the regulatory scenarios considered. This results in a distribution of regulatory burden that is progressive over the first four income quintiles. However, in most (86%) of the scenarios the costs as a share of income are lower for the highest income quintile than for at least one of the preceding quintiles. Notable exceptions are regulations in fossil fuel extraction sectors where the source-side incidence is estimated to be strong enough to result in a progressive distribution of costs across the entire income distribution due to a significant share of the costs being passed on to owners of the affected natural resources.

Given that the distribution of regulatory costs relative to income is not increasing across the entire income distribution, we use the Suits index to make quantitative comparisons regarding the average progressivity/regressivity of the incidence of regulatory costs. Based on the Suits index, we find that, on average, the distribution of regulatory costs is slightly progressive for around two thirds of the regulatory scenarios considered. This is because we find that a substantial share of regulatory costs is passed on to households through lower returns to primary factors of production, which disproportionately affect high-income households. Meanwhile low-income households after-tax and transfer income is partially protected from regulatory costs passed through on the use side due to a compensating effect of indexed transfer payments on the source side. Together, these effects dominate the distribution of regulatory costs. For the scenarios considered, we find distribution of regulatory costs through the source side is substantially more important for determining the overall incidence of costs compared to the distribution of regulatory costs through the use side. This result has important implications for the common empirical approach to estimating distributional impacts that focuses primarily on the distribution of costs through consumption prices and suggests that more attention should be paid to impacts of regulations on sources of income.

However, we do find that in some cases the use-side incidence has a notable effect on the overall distribution of costs. These cases include regulations affecting utilities that produce and distribute electricity, waste, water, and sewage services, refined petroleum, and food and beverage manufacturing. These are sectors with high shares of production being final consumption and where demand is both highly inelastic and relatively similar across households leading to most of the costs being passed through a regressive use side. When focusing on the use side we find the distribution of costs for regulations in these sectors to be notably regressive, consistent with prior studies (e.g., Burtraw et al., 2010; Hasset et al., 2009). Though, we find that even for policies in these sectors the source-side effects are of first-order importance for determining the overall distribution of regulatory costs.

A common characteristic of many federal environmental regulations is that they are only applicable to new sources of emissions (e.g., grandfathering). Under this type of vintage differentiation, the regulatory costs for new sources act as a new barrier to entry on which owners of existing sources can extract rents. Since these rents are predominately captured by high-income households, in most cases vintage differentiation leads to a notably more regressive distribution of costs relative to a regulation that affects all sources equally. An exception is the case of capital-intensive abatement technologies, where the scarcity rents are dominated by reduced returns to new capital that is now less productive under the regulation. The regressive effect of vintage differentiation is greatest for regulations requiring labor-intensive abatement activities where the source-side costs fall predominantly on labor, which is a relatively greater source of income for middle-income households and does not offset the scarcity rents captured by owners of existing sources.

It should be noted that, based on the illustrative nature of our investigation, we apply the simplifying assumption that the cost of abatement is the same for new and existing sources. While this is the case for some regulations, one stated motivation for vintage differentiation is that pollution abatement is cheaper for new sources that can build their production facility with the environmental regulation in mind instead of retrofitting an existing facility. For a regulation affecting all sources with a common stringency, this would lead to a case where the costs are differentiated across capital vintage, with higher costs falling on production associated with existing capital. The limited mobility of existing capital means that the effect of the cost differential will likely be to increase the share of costs borne by capital owners, thereby increasing the regressivity of a regulation affecting all sources with a common stringency above what we estimate. If the use of vintage differentiation works to equate the abatement costs between sources the incidence may be more in line with our results for the all source regulations.

In this paper, we focus on the vertical incidence of regulatory costs across income quintiles and the role of the source side in determining that incidence. When interpreting our results, it is important to note there is a great deal of heterogeneity within income quintiles. For example, a significant percentage of the households in the lowest income quintile are in college or retired and would be expected to currently have low levels of money income (Crain and Wilson, 2017). These households are combined in a single quintile with the perennially poor even though lifetime wealth across those two groups may be substantially different. Furthermore, household size and location are important for determining the lifestyle afforded to a household based on a given level of income. Future research examining whether and how the source-side effects impact the horizontal incidence within quintiles is warranted. This could be accomplished by further disaggregating the representative households within the quintiles (e.g., Rausch et al., 2011; Cronin et al., 2017) or through using different classifications of households, such as on the basis of lifetime income or consumption rather than contemporaneous annual income (Fullerton and Metcalf, 2002; Fullerton et al., 2011).

Our study is intended to be a broad look at the incidence of typical command-and-control environmental regulations and therefore, some simplifying assumption were made that should be revisited in a detailed policy analysis. First, 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 distribution of costs. The presence of close substitutes is likely to limit price increases in the regulated sector leading the source-side incidence to have even greater dominance, but this is worth further investigation. Second, we consider regulations whose cost of compliance is equal across space. In practice, environmental regulations often have compliance costs that are differentiated across space. These regional differences may have important implications for the incidence of costs.

Finally, in this paper we focus on the distribution of regulatory costs and the strength of source-side effects in defining the incidence for technology mandates. However, it is important to note that a complete analysis of the incidence of environmental regulations should consider both the distribution of costs and benefits over the populations of interest. Some benefits may be separable in households' utility functions, as we implicitly assume. Though, in some cases the beneficial impacts of pollution abatement could affect equilibrium in the economy through multiple channels (Williams, 2002; Carbone and Smith, 2008; Marten and Newbold, 2017). The degree to which the beneficial impacts interact with regulatory costs in equilibrium and affect the incidence of environmental policies remains an important question for future research.

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Appendix

A Model Calibration

The social accounting matrix is built from the 2016 state level accounts in the IMPLAN dataset.[22] The IMPLAN dataset is extended in three ways. First, ad valorem taxes for labor and capital income are added to the dataset (see Appendix B). 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).[23] We adopt the substitution elasticities in the intra-temporal utility function's energy bundle (*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

[22] IMPLAN Group, LLC, 16740 Birkdale Commons Parkway, Suite 206, Huntersville, NC 28078; www.IMPLAN.com .
[23] 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).

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 Specification of Marginal and Average Personal Income Tax Rates

The model we use is the same as detailed in Marten and Garbaccio (2018), expect for improvements in the representation of taxes to more accurately represent the share of income index by labor and capital prices and an update to more recent estimates of state and local sales tax rates. In this section we describe the tax structure of the updated model. The model explicitly includes consumption, tc_r, personal labor income tax, $tl_{r,h}$, personal capital income tax, $tr_{r,h}$, other business taxes/subsidies, $ty_{r,s}$, and corporate income tax, $tk_{r,h}$. Production taxes net of any subsidies, $ty_{r,s}$, are based on the average rate observed in the IMPLAN database. The corporate income tax, $tk_{r,h}$, is assumed to be constant across the U.S. and is based on an assessment of the average effective marginal corporate income tax rate by the U.S. Congressional Budget Office (CBO, 2017). Consumption taxes are based on estimates of the combined local and state consumption tax rates from the Tax Foundation.[24] The tax rates on corporate income and consumption are presented in Table 3.

[24] https://taxfoundation.org/state-and-local-sales-tax-rates-2018/

Table 3: Tax Rates on Corporate Income and Consumption

Region	$tk_{r,h}$	tc_r
nen	0.19	0.06
mat	0.19	0.07
enc	0.19	0.07
wnc	0.19	0.08
sat	0.19	0.07
esc	0.19	0.08
wsc	0.19	0.09
mnt	0.19	0.07
pac	0.19	0.08

Personal income taxes on labor and capital incomes are differentiated across regions and households. We represent effective marginal personal income tax rates separately for capital and labor income to better capture the average marginal taxes paid on an additional dollar of wage income versus investment income for the population underlying the representative household. Effective marginal Federal Insurance Contribution Act (FICA) taxes are also differentiated across regions and households. This allows the payroll tax rates to capture the annual limit on Old Age and Survivor's Insurance (OASI) taxes, which would not be possible if the payroll taxes were collected on the firm side based on the model's structure. Data from the U.S. Census Bureau's Current Population Survey (CPS) Annual Social and Economic Supplement (ASEC) is used to create a representative sample of tax returns. These sample returns are then run through NBER's Taxsim model version 27 to estimate marginal tax rates for wage income, FICA, and long-term capital gains income for each sample return (Feenberg and Coutts, 1993).[25] For each region and household we compute the weighted average effective marginal tax rate from the sample returns by weighting the Taxsim results by the CPS ASEC earned income and applying the supplement weights.

From the CPS, the filing status variable (filestat) and the dependent status variable (dep_stat) are used to distinguish between single/head of household taxpayers and dependent taxpayers. All married taxpayers are assumed to file jointly, and the person records for each couple are identified using the a_spouse variable. The dep_row variable in the CPS is used to assign non-filing dependents to taxpayers, along with the ages of the dependents. This information is used to populate the Taxsim variables used to assess personal exemptions, the Dependent Care Credit, the Child Credit, and the Earned Income Tax Credit.

[25] http://users.nber.org/~taxsim/taxsim27/

The income variables in the CPS ASEC are mapped to the Taxsim variables as described in Table 4. For married couples, all income values entered into Taxsim are the joint earnings, except in the case of wage and salary income, which are kept separate. The CPS no longer included imputed capital gains and therefore, they are omitted from the submission to Taxsim. This limitation may bias the weighted average effective marginal tax rates downwards for the household representing the top income quintile (where nearly all capital gains accrue) if the inclusion would cause some household to be in a higher tax bracket.

Table 4: CPS to NBER Taxsim Income Mapping

Taxsim Variable	Description	CPS Variable(s)[26]
pwage	Wage and salary income of primary taxpayer	ws_val, semp_val, frse_val
swage	Wage and salary income of spouse	ws_val, semp_val, frse_val
dividends	Qualified dividend income	div_val
stcg	Short term capital gains or losses	NA[27]
ltcg	Long term capital gains or losses	NA[28]
otherprop	Other property income	rnt_val
nonprop	Other non-property income	oi_val, ed_val
pensions	Taxable pensions and IRA distributions	rtm_val
gssi	Gross social security benefits	ss_val, ssi_val, srvs_val, dsab_val
ui	Unemployment compensation	uc_val
transfers	Other non-taxable transfer income	paw_val, wc_val, vet_val, csp_val, fin_val

The implicit deductions for each filer are computed as the difference between adjusted gross income (agi) and taxable income (tax_inc) as reported in the CPS minus personal exemption deductions accounting for the phase out. From this value we subtract property and state taxes and submit the higher of this value or zero to Taxsim as potential sources of itemized deductions. Property taxes in the CPS ASEC (prop_tax) are associated with household records so we divide those taxes equally amongst all tax filing units in a household.

For each representative filer, Taxsim returns the effective marginal tax rate for primary earner wage income. Using the CPS ASEC person weights and primary earner wages, a weighted average of the effective marginal tax rates for wage income are computed for each region and representative household

[26] Except for the primary and spouse wage and salary income each Taxsim variable is the sum of the CPS variables for both the primary taxpayer and their spouse for married taxpayers.
[27] The CPS ASEC does not include information on imputed capital gains after 2010.
[28] *Ibid*.

in the model. A similar exercise is conducted for long-term capital gains taxes, though the weighted average uses dividend and interest income as a proxy for capital income.

The personal labor income tax rates by region and household are presented in Figure 11, the FICA tax rates are presented in Figure 12, and the personal capital tax rates bare presented in Figure 13. The crossbars represent the national income weighted average effective marginal tax rate, for the specific income category.

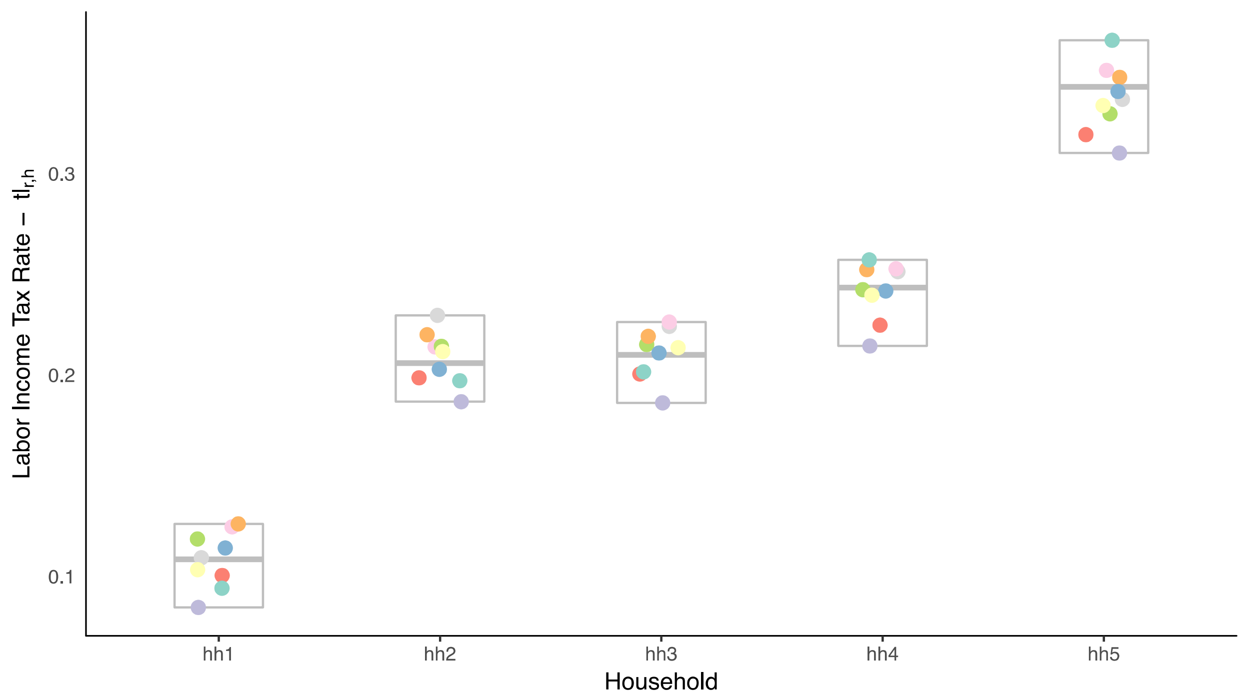


Figure 11: Labor Income Effective Marginal Tax Rate by Household and Region

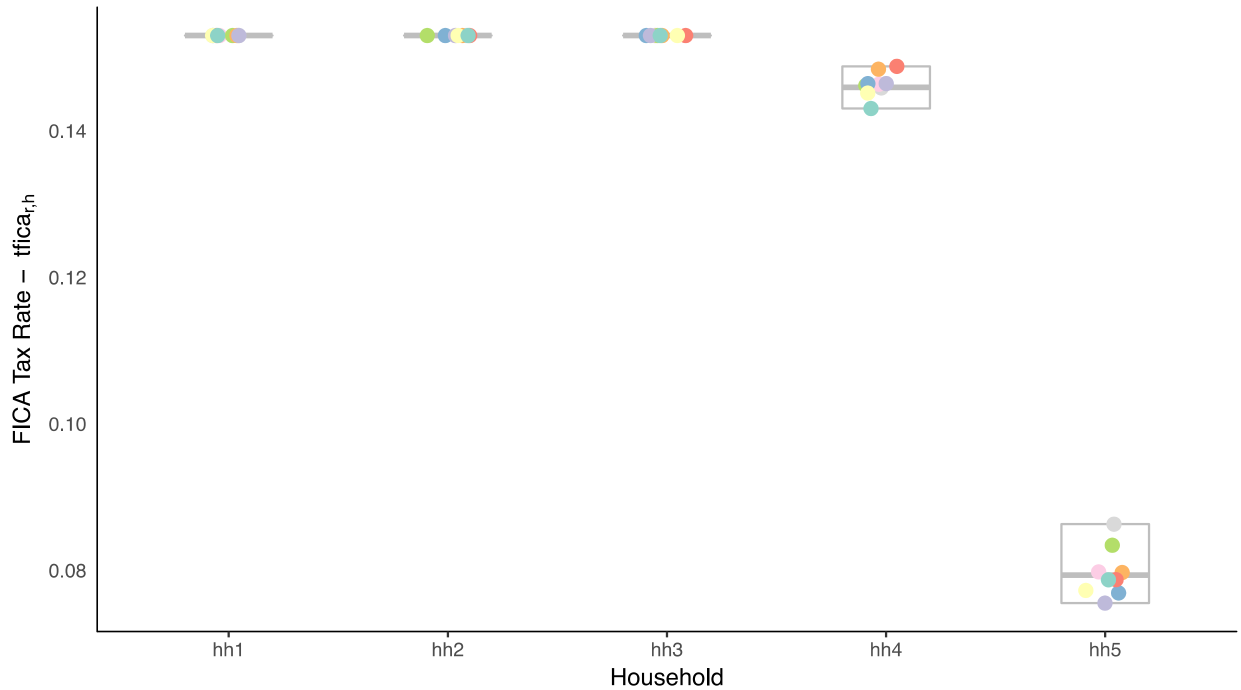


Figure 12: FICA Effective Marginal Tax Rate by Household and Region

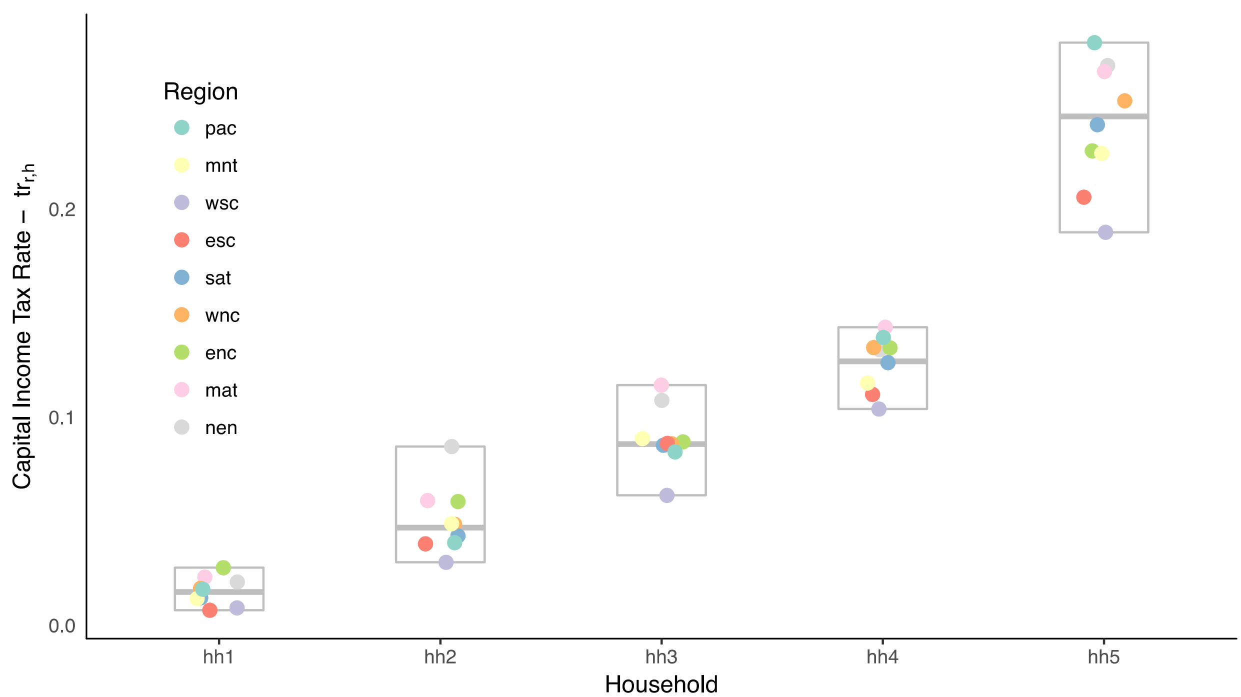


Figure 13: Capital Income Effective Marginal Tax Rate by Household and Region

To calibrate the factor price index transfer from government to households to match the average tax rate we use the estimate of personal income tax payments in the IMPLAN dataset, $income\_tax0_{r,h}$. The personal income tax payment is split between labor and capital sources based on their share of pre-tax factor income, such that

$$tl\_refund_{t,r,h} = tl_{r,h} l0_{r,h} \left[1 - \frac{\max\left(income\_tax0_{r,h}, 0\right)}{tl_{r,h} l0_{r,h} + tr_{r,h}\left(re\_ex0_{r,h} + re0_{r,h} + \sum_s rese0_{r,s,h} \right)} \right] \quad (2)$$

and

$$tr\_refund_{t,r,h} = tr_{r,h}\left(re\_ex0_{r,h} + re0_{r,h} + \sum_s rese0_{r,s,h} \right) \left[1 - \frac{\max\left(income\_tax0_{r,h}, 0\right)}{tl_{r,h} l0_{r,h} + tr_{r,h}\left(re\_ex0_{r,h} + re0_{r,h} + \sum_s rese0_{r,s,h} \right)} \right], \quad (3)$$

where $l0_{r,h}$ is benchmark year labor income, $re\_ex0_{r,h}$ is benchmark year income from extant capital, $re0_{r,h}$ is benchmark year income from new capital, and $rese0_{r,s,h}$ is income from fixed factor resources employed in sector s. The transfers are assumed to grow at the balanced growth rate and The transfer $tl\_refund_{t,r,h}$ is index at the wage rate $pl_{t,r}$ and the transfer $tr\_refund_{t,r,h}$ is indexed by an index of capital prices

$$prh\_ind_{t,r,h} = \frac{pr_{t,r} r0_{r,h} + pr\_ex\_agg_{t,r} kh\_ex0_{r,h} + \sum_s pres_{t,r,s} resh0_{r,s}}{r0_{r,h} + kh\_ex0_{r,h} + \sum_s resh0_{r,s}},$$

where $pr\_ex\_agg_{t,r}$ is the return to extant capital, $pr_{t,r}$ is the return to new capital, and $pres_{t,r,s}$ is the return to fixed factors used in sector s.

C Regulation Input Bias Specification

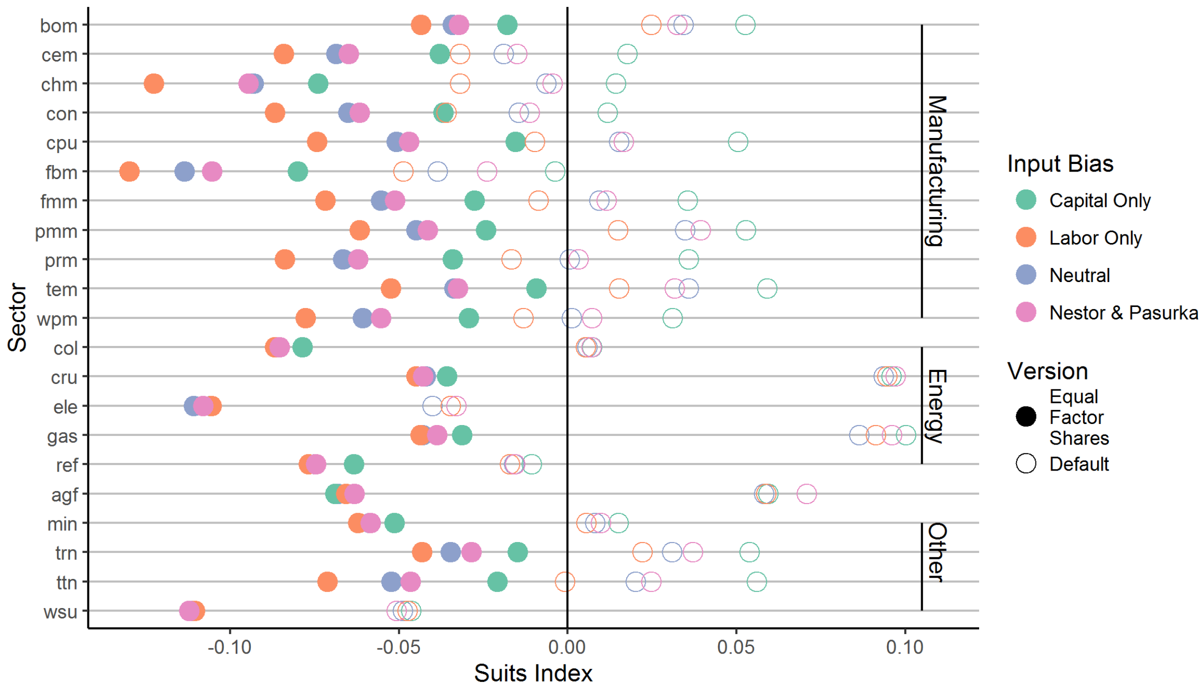
Table 5: Alternative Input Shares for Abatement Technology

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	--

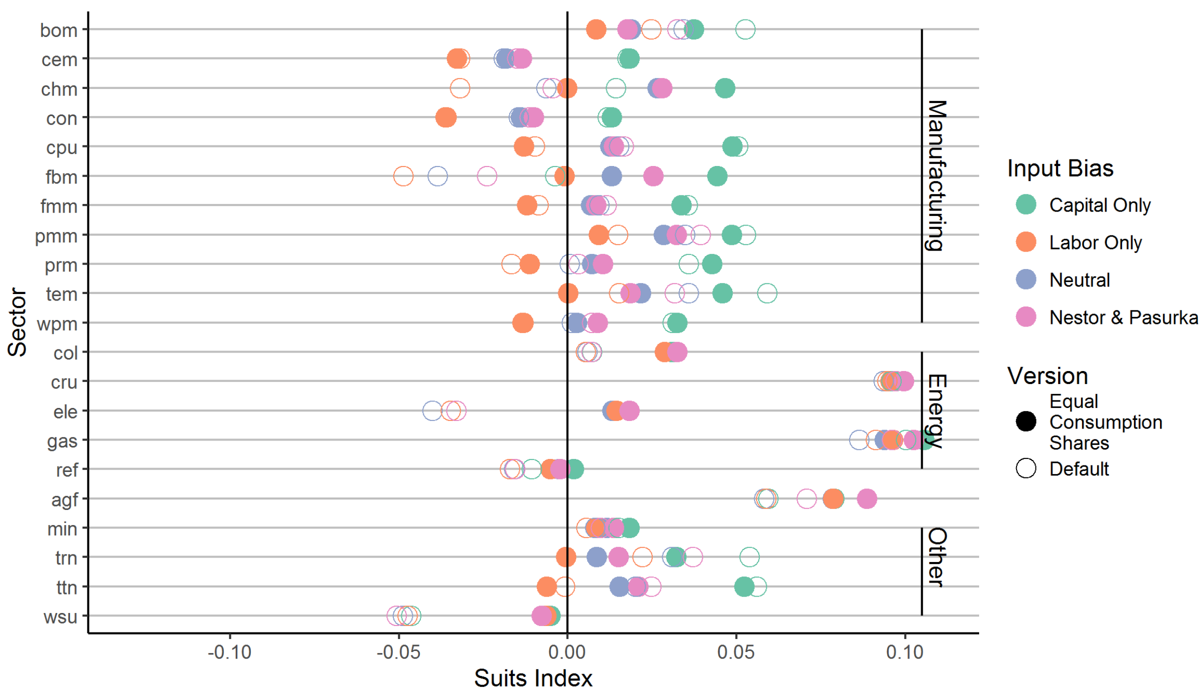
D Sensitivity to Putty-Clay Capital Specification

Figure 14 presents the use and source-side decompositions for the case were existing capital is fully malleable (i.e., no modeling of partial putty-clay capital). The hollow points in the figure are denoted as "Default" and in this case refer to the Suits index for the overall distribution of regulatory costs when the model is run without the partial putty clay structure. These results pertain to the scenarios in which all sources of production are subject to the regulation.

In general, the results are similar to the case where extant capital is assumed to have very limited mobility (Figure 9). The source-side effects still dominate the overall distribution of costs as may be seen from the similarity between the source-side sensitivity in Figure 14b and the hollow points representing the Suits index for the overall incidence. The main difference is that the presence of extant capital with very limited mobility is no longer the dominant factor in determining the share of regulatory costs that are passed on through factor prices. Under the extreme assumption that all capital is malleable, even in the near term, the input composition of compliance activities has a greater impact on the share of costs passed on through the source side. However, the source-side effects still dominate the shape of the overall distribution.



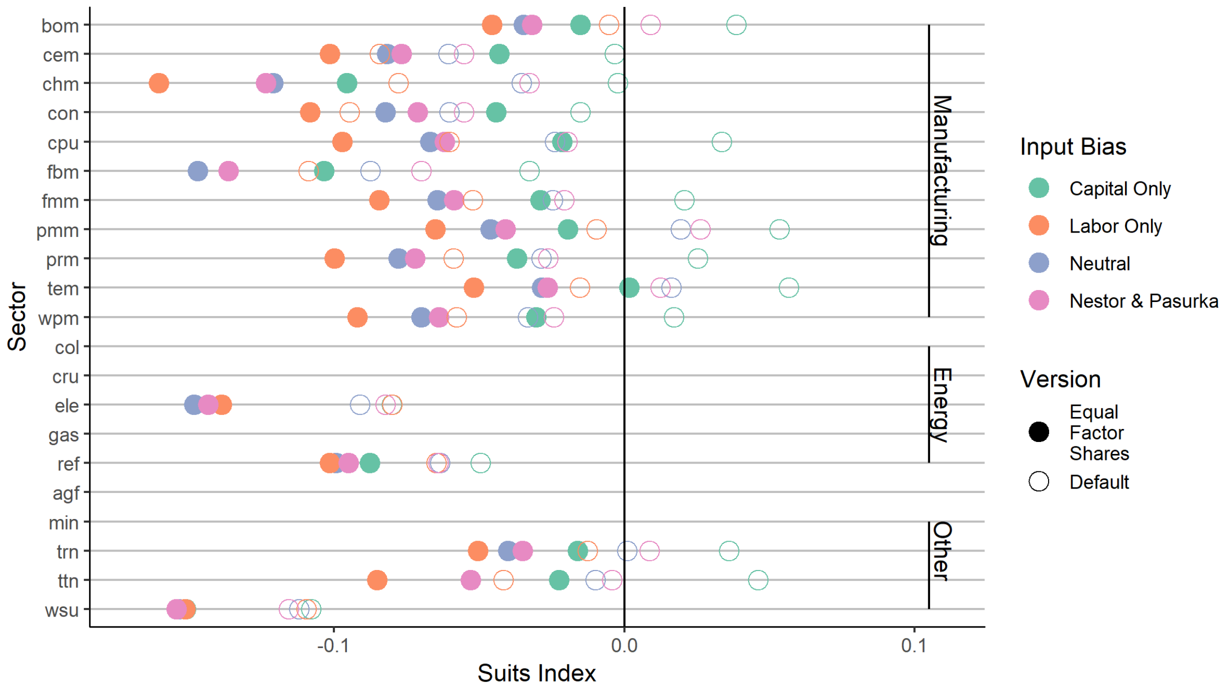
(a) Equal After-Tax Factor Shares



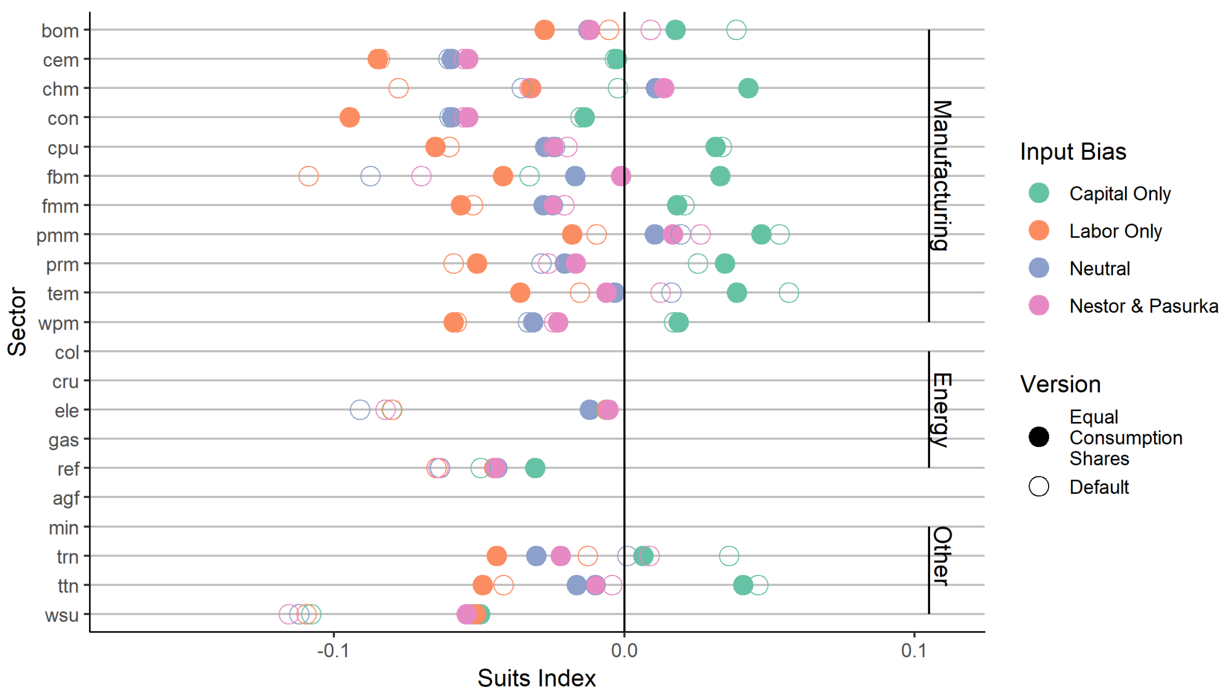
(b) Equal Consumption Shares

Figure 14: Use- and Source-side Suits Index for without Putty-Clay Capital

E Use- and Source-Side Decomposition for New Source Regulations



(a) Equal After-Tax Factor Shares



(b) Equal Consumption Shares

Figure 15: Use- and Source-Side Suits Index for New Source Regulations