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Evaluating Economy-wide Effects of Power Sector Regulations Using the SAGE Model*

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Abstract

We develop a novel methodology for linking a detailed industry model, such as the Integrated Planning Model (IPM) of the electricity sector, with the U.S. Environmental Protection Agency's computable general equilibrium model, SAGE, to estimate the economy-wide social costs and distributional impacts of an environmental regulation when an iterative linkage between models is not possible. We demonstrate the linking approach using stylized compliance costs that are consistent with the types of model outputs typically available from a technology-rich industry model to calibrate an identical equilibrium response in a corresponding partial equilibrium sub-model of SAGE. The calibrated parameters are then passed to the full version of SAGE to estimate general equilibrium impacts. This methodology allows us to translate partial equilibrium impacts into economy-wide impacts while retaining consistency in underlying compliance behavior. The linked framework provides a means of calculating indirect sectoral impacts, aggregate welfare impacts, and distributional outcomes that capture both income and expenditure effects for heterogeneous households. In our stylized example, we find that aggregate social costs are greater than calibrated engineering costs of compliance by approximately 21% and assumed sector-specific partial equilibrium costs by 29%. We also discuss data challenges of operationalizing this methodology in a real-world setting.

JEL Codes: C68; D58; D61; L94; Q43; Q58

Keywords: Computable General Equilibrium; Social Opportunity Cost; Electricity Sector; Aggregate Energy Consumption; Environmental Regulation

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1 Introduction

Consistent with its authorizing statutes, the United States Environmental Protection Agency (EPA) frequently promulgates regulations in specific industries that limit the emissions of one or more pollutants. Some of these regulations may have compliance costs that are of sufficient size that the regulation may have meaningful impacts on prices and outputs. For example, the 2012 Mercury and Air Toxics Standard, which required reductions in air pollution from electricity generators, was estimated to require around 10 billion dollars in annualized compliance costs (2007 dollars).[1] Regulations on industries, such as the electricity sector, that provide inputs to many other sectors in the economy can also result in potentially meaningful indirect impacts in other parts of the economy. These indirect impacts can be important for estimating the ultimate impact on household welfare.

In assessing the compliance costs of electricity sector regulations, the EPA has traditionally relied on the Integrated Planning Model (IPM). IPM is a highly detailed, partial equilibrium (PE) linear programming model of the power sector and related energy markets. When this model is used in regulatory analysis, the estimates of compliance costs are typically assumed to be an approximation of social costs, or the sum of all opportunity costs, that may result from the regulation in the present and future.[2] However, social costs may be higher or lower than compliance costs for a number of reasons, including interactions with pre-existing distortions in the economy, shifts in the demand for electricity in response to the rule, and because certain compliance costs may capture shifts in rents (SAB, 2017).

A key question in understanding the difference between compliance costs and social costs is whether the expected effects outside of the regulated sector are relatively large and warrant explicit evaluation (Hahn and Hird, 1991). Increases in prices due to regulatory compliance activities can have indirect effects in other markets as other sectors have additional incentive to substitute away from those inputs in their production processes. Electricity is one such example. There may also be impacts in upstream industries that supply goods and services to the regulated sector, labor markets in response to changes in factor prices, and household demand due to changes in end-use prices. It is not possible to quantitatively characterize these potential effects simultaneously without an economy-wide modeling approach. Research suggests that the magnitude and direction of the net cost impact of these additional effects depend on the form of regulation, the sector directly regulated, and interactions with pre-existing distortions in the economy (Goulder et al., 1999; Williams III, 2002; Marten et al., 2019; Goulder and Williams III, 2003).

The EPA's Science Advisory Board (SAB) recommended the use of computable general equilibrium (CGE) models to estimate the economy-wide social costs of regulations (SAB, 2017). Broadly, CGE models are a class of economy-wide models that can be used to evaluate the impacts of an economic shock, such as a major regulation, across multiple sectors, regions, and households. Typically, these

[1] https://www3.epa.gov/ttnecas1/regdata/RIAs/matsriafinal.pdf

[2] In this setting, compliance costs are defined as incremental costs to the regulated sector needed to meet regulatory requirements. For more on the relationship between compliance costs and social costs, see Chapter 8 in EPA (2010) and EPA (2015).

types of models are characterized by defining a set of equilibrium conditions in which supply equals demand in all markets, firms are perfectly competitive, and households satisfy their budget constraints. When a regulation alters any one of these conditions, the model solves for a new set of relative prices and quantities to return the economy to equilibrium. Social costs can be estimated by comparing variables in the pre-regulation "baseline" equilibrium to those in the post-regulation "simulated" equilibrium. The SAB recommended that the EPA begin to integrate CGE modeling into its suite of tools available for regulatory analysis to support more comprehensive assessments of potential regulatory impacts. The SAB also noted that the case for using a CGE model to evaluate the costs of a regulation is strongest when the costs of compliance are expected to be large in magnitude and the sector is strongly linked to the broader economy. For regulatory actions directed toward smaller industries or a relatively small subset of facilities within a larger industry - the majority of EPA regulations - the modeling framework would likely be ill-suited for capturing social costs.

In particular, the SAB advised that general equilibrium (GE) modeling should be regarded as a complement to the engineering-based or PE assessments of compliance costs traditionally performed by the EPA. The resolution offered in many CGE models is often too aggregate to adequately model important compliance pathways or nuances of the regulatory requirements. In such cases, the SAB recommended linking a detailed sector model with a CGE model. The detailed sector model can be used to capture expected compliance pathways in the regulated sector, while the CGE model can be used to capture indirect effects in the rest of the economy and quantify social costs and distributional impacts inclusive of broader economic effects. This allows the analysis to benefit from the comparative advantages of both modeling frameworks. The SAB noted that "it will often be necessary and appropriate for EPA to link a GE model having a modest degree of detail to one or more PE models having greater detail", and that while linked models will always have some level of inconsistency between definitions of variables and parameters, it is likely acceptable given the significant added value from the linked framework (SAB, 2017).

In response to the SAB recommendations, the EPA developed the SAGE (SAGE is an Applied General Equilibrium) model of the United States economy (Marten et al., 2023). SAGE is a multi-sector, multi-region, forward-looking intertemporal CGE model with heterogeneous households. However, due to computational and data restrictions of capturing behavior exhibiting perfect foresight with sub-national detail and heterogeneous households, the model has a relatively aggregate representation at the sectoral level. For example, the electricity sector is represented as a single sector composed of aggregate electricity generation, transmission, and distribution. By linking the SAGE model to a detailed PE model of the regulated sector (e.g., IPM), it is possible to evaluate the economy-wide impacts of a regulation using the CGE model, while allowing the modeled compliance pathway to be primarily driven by the detailed sector representation of the PE model.

In this paper, we develop a methodology for linking SAGE with a detailed sector model, such as IPM, to calculate both the social and distributional costs associated with an illustrative policy scenario. Our focus is an environment where the sector model is either proprietary (i.e., owned and operated by a private entity under contract to the EPA) or too computationally expensive to allow the use of fully iterative linking techniques. Traditional model linking methodologies rely on "soft-linked" one-way, summary function, or iterative approaches (SAB, 2017). While a simple one-way soft linkage is almost always possible, the SAB noted that structural inconsistencies between models will make it difficult to translate sector model results into CGE model inputs without being arbitrary and inconsistent. On the other hand, while an iterative approach provides the most robust linkage, it is may not possible because detailed sector models, such as IPM, that are sometimes used for regulatory analysis are proprietary and/or computationally and resource intensive. A summary function approach summarizes key economic information from a bottom-up model, such as the marginal abatement cost curve, in terms of an aggregated functional relationship and embeds it in a CGE model. While the summary function approach avoids the need to concurrently run the two models in an iterative fashion, at the cost of some consistency in the linkage, it does not necessarily avoid the computational and resource constraints in some situations. Establishing the summary function may itself require running the sector model a considerable number of times, especially in cases where there are a large number of policy variables (e.g., emission standards, sub-categorization, multi-phased standards).

In this paper, we develop a "hybrid" linkage approach using elements of several traditional linking approaches. Our approach seeks to align the detailed sector model with a corresponding PE sub-model of SAGE to calibrate model inputs (e.g., a policy shock) that produces incremental costs identical to the sector model. By using incremental costs ($\Delta p * q$), we circumvent many of the issues of a one-way model linking exercise that directly assigns price and quantity changes from one model to another. This methodology allows us to translate PE incremental costs in the regulated sector into social costs that are reflective of economy-wide impacts and compare their relative magnitudes. As opposed to a naive calibration approach that treats incremental costs from the sector model as not inclusive of substitution effects, our hybrid approach accounts for the robustness of the sector modeling and potential differences in the way the models characterize the regulated sector.

We illustrate the approach assuming stylized incremental PE costs for generators to meet regulatory requirements in the electricity sector that are consistent with the types of model outputs typically available from IPM. In our simplified setting, we produce an example where aggregate social costs are approximately 21% greater than calibrated engineering costs of compliance and 29% greater than stylized PE costs assumed in this scenario. This ratio of the social costs to engineering compliance costs is consistent with the findings in Marten et al. (2019). When estimating the distribution of social costs across households with different income levels, the GE model allows us to capture the effect of the regulation on both household income and expenditures. Under the stylized policy scenario, we find that poorer households are relatively more burdened by rising electricity sector prices, whereas richer households are relatively more impacted by reductions in the value of their investments. On average, the stylized policy scenario is expected to cost households in the top income quintile approximately 125% more per year than households in the lowest income quintile on an absolute basis. Furthermore, we illustrate the value added of the linked approach relative to a naive calibration approach that treats incremental PE costs as not inclusive of substitution effects. We show that doing so elicits alternative partial equilibrium compliance behavior and an under-estimate of social costs.

Our proposed methodology has several advantages and some potential limitations. First, this approach allows us to explicitly compare engineering estimates of compliance costs with incremental PE costs from a sector-specific model and social costs from SAGE. Existing literature has compared engineering costs of compliance with social costs, but the intermediary link has been relatively unstudied in the context of environmental regulation (Goulder et al., 1999; Williams III, 2002; Marten et al., 2019; Goulder and Williams III, 2003). Second, the approach does not require major changes to the sector modeling that is typically conducted for major rules, thus minimizing potential resource burdens. Another benefit of the approach is its reproducibility. The EPA has often relied on highly detailed but proprietary sector models to generate compliance cost estimates (e.g., IPM). Iteratively linking SAGE with a proprietary sector model would limit the ability to reproduce the results of the economy-wide analysis. However, because SAGE is an open source CGE model and outputs (i.e., incremental costs) from the sector model used in support of a rulemaking are typically published in the docket, the modeling involved in producing the social costs and distributional impacts with SAGE will be reproducible.

The hybrid linking approach is not without potential limitations. Since a full iterative link between the sectoral model and SAGE is not currently feasible, as discussed above, we are unable to test the efficacy of the hybrid approach relative to the iterative approach. We save this explicit comparison for future research, where a more tractable open source sector model could be used to evaluate the approach. Another potential limitation of any model linking approach is the data uncertainties in translating outputs of one model to inputs in another. While our approach alleviates many of the conventional issues associated with translating model inputs and outputs, a later section of this paper discusses potential elements of data translation that may warrant additional attention.

The remainder of the paper is organized as follows. In Section 2, we provide a brief overview of the SAGE model. We introduce the hybrid linkage approach in Section 3. In Section 4, we discuss how SAGE-PE can be tailored to analyze a hypothetical regulation in the electricity sector assuming modeling outputs similar to those produced by IPM and report the outcomes of an illustrative policy scenario. The paper concludes with a discussion of data requirements for the framework in a real-world setting, potential limitations, and suggestions for future research in Section 5.

2 Overview of the SAGE Model

The SAGE model is documented in Marten et al. (2023) and is an intertemporal dynamic CGE model of the United States economy. Table 1 summarizes its dimensions over modeled time periods, sectors, regions, household types (denominated by income level), and capital vintage. The economy is modeled in 5-year time steps from 2016-2081. Twenty-three sectors are modeled that encompass the entirety of the U.S. economy with resolution particularly focused on the energy and manufacturing sectors. The model captures subnational regional representation within the United States in the form of four Census Regions where each region has region-specific production functions for each of the twenty-three sectors and household preferences for the five household income types.

Table 1: SAGE Dimensions

Time Periods	**Sectors**	**Census Regions**	**Households (income 2016$)**	**Capital Vintage**
2016-2081 (5-year time steps)	Agriculture, forestry, fishing and hunting Crude oil Coal mining Metal ore and nonmetalic mineral mining Electric power Natural gas Water, sewage, and other utilities Construction Food and beverage manufacturing Wood product manufacturing Petroleum refineries Chemical manufacturing Plastics and rubber products manufacturing Cement manufacturing Primary metal manufacturing Fabricated metal product manufacturing Electronics and technology manufacturing Transportation equipment manufacturing Other manufacturing Transportation Truck transportation Services Healthcare services	Northeast South Midwest West	<30k 30-50k 50-70k 70-150k >150k	Extant New

SAGE models sectoral production assuming perfectly competitive representative firms maximize profits subject to technology restrictions. The model distinguishes physical capital by its age to limit the transition of existing capital already present in the reference year (i.e., first time period of the model) between sectors and production processes. This approach, called partial putty clay, models existing (or extant) capital in the reference year differently from new capital formed after the reference year. Extant capital is assumed to be relatively inflexible in its ability to accommodate changes in production processes and cross-sectoral uses relative to new capital, which can be shifted across sectors and substituted with other inputs. Production with extant capital is assumed to follow a Leontief structure where inputs are used in fixed proportions.

Production with new capital is modeled as nested constant elasticity of substitution (CES) functions that can differentially characterize substitution possibilities between classes of inputs. For most sectors in the model, the top level nest combines a non-energy materials composite with a value added-energy composite. Non-energy material inputs (all non-factor inputs to production include both domestically and internationally produced varieties) are assumed to be used in fixed proportions. The value added-energy composite combines a capital-labor composite with a primary energy-electricity composite. The lower level nests characterize substitution between capital and labor, electricity and a primary energy composite, and amongst primary energy inputs. All substitution elasticities governing the substitution possibilities in this framework are adapted from the best available estimates in the economics literature. For resource extraction (crude oil, natural gas, coal, and other mining) and agriculture sectors, the model assumes an additional factor input to represent finite natural resources at the top level of the production structure. The additional substitution elasticities are calibrated to supply elasticities from the literature.

Households are assumed to maximize their intertemporal (across time steps) welfare subject to a budget constraint composed of factor incomes and transfers. Intertemporal welfare consists of a discounted stream of iso-elastic utility across modeled years. Intra-temporal (within time step) utility is governed by a nested CES-LES (linear expenditure system) function. The top level substitution elasticity is calibrated to labor supply elasticities taken from the literature and the lower level LES system governing preference for commodities is calibrated to estimated income elasticities (methodology adapted from Aguiar and Bils (2015)). A single government agent representing local, state and federal entities is assumed to levy taxes on labor and capital earnings and production in the form of indirect business taxes. The model assumes a balanced government budget, inclusive of an exogenous debt projection, such that any budget excess or shortfall in response to a policy shock is recycled as lump sum payments to or from households. Households are endowed with factors of production (e.g., time and capital) on which they earn incomes. Population, and in turn the time endowment, grows exogenously over time and households are assumed to supply labor within the region in which they reside. Household ownership of capital stock grows endogenously through savings, where household investment is mobile across regions. However, once installed, capital is assumed to be fixed to a model region (independent of its vintage). The capital stock is augmented through investment in the previous period.

SAGE models the U.S. economy as a large open economy allowing for changes in the U.S. to impact world prices. Instead of directly modeling trade flows between countries, SAGE operationalizes the large open economy specification in a reduced form setting by calibrating a series of import supply and export demand functions to price elasticities consistent with the GTAP modeling framework (Aguiar et al., 2016; Lanz and Rutherford, 2016). The model characterizes imports from and exports to the international economy using the Armington assumption that defines preferences for regionally differentiated goods and is also calibrated to elasticities from the GTAP database (Armington, 1969). Trade within the U.S. is modeled as a pooled national market.

The SAGE model is based on several underlying datasets and projections. The core economic accounts are based on IMPLAN 2016, but have been augmented to reflect economic estimates from the Energy Information Administration, Department of Interior, Department of Agriculture, Bureau of Economic Analysis, Census, Bureau of Labor Statistics, Congressional Budget Office, and the National Bureau of Economic Research. The model is solved as a mixed complementarity problem akin to Rutherford (1995). SAGE has been peer reviewed by the EPA's SAB to ensure that the model is consistent with economic theory and reflects the latest science (SAB, 2020). The report commended the agency in its development of SAGE, and included recommendations for refining and improving the model. All tier 1 recommendations, or those that the SAB advised the EPA to incorporate before using the model in regulatory analysis, have been addressed as of version 2.0.1 of the model.[3] For this modeling exercise, we rely on version 2.1.0, which incorporates additional minor updates over version 2.0.1.

3 Overview of Linking SAGE with a Sector Model

In our context, an ideal linkage framework would have the following characteristics. Foremost, the linked framework should be theoretically sensible and produce reasonable results. The framework should provide for a single authoritative PE solution that is consistent across both models even when an iterative linkage is not feasible. The CGE model solution should reflect the information the more detailed sector model provides on the engineering costs of compliance, the composition of the sector (e.g., generation shifting in the electricity sector), prices, and other market impacts such as impacts on markets for fuels, even when the sector model is proprietary and only model outputs are available. The framework should also be practically implementable within the relatively short development time frame typically available for regulatory analysis and limit the need for additional resources. Finally, the CGE model solution should be publicly available and reproducible.

3.1 Traditional PE-CGE Linking Approaches

SAB (2017) describes four main approaches for linking CGE models with sector models that have been considered in the economics literature: (1) soft linking, (2) summary function approach, (3) sequential calibration, and (4) hard linking or disaggregation of the CGE model. A soft linkage typically refers to a case where information from a PE model is fed into a CGE model. Such an approach can be done in a one-way or iterative approach. This type of linkage is most common when the models are complex and/or differences in structure prevent integrating the two frameworks together.[4] The summary function approach summarizes information from a detailed sector model and implements a reduced-form representation directly within the CGE model. For instance, some papers have used this approach to incorporate marginal abatement cost curves within the CGE model (e.g., Morris et al. (2012)) while others recalibrate CGE responses to mimic PE responses by incorporating additional information like supply elasticities to align the modeling frameworks (Pelikan et al., 2015). Sequential calibration, introduced by Böhringer and Rutherford (2008) and Böhringer and Rutherford (2009), relies on features of the mixed complementarity formulation to sequentially approximate responses between the modeling frameworks to converge to an equilibrium solution. The final approach of model linking is simply to embed the detailed model into the top-down economic model, or to integrate bottom-up technologies into the CGE model by disaggregating the sector of interest.

[3] For the EPA's responses to SAB comments, see https://www.epa.gov/node/266413.

[4] Some modelers have cautioned the use of an iterative soft link noting that these frameworks can have difficulties converging given structural and accounting differences in the linked models (Böhringer and Rutherford, 2009).

However, these traditional methods do not align with the characteristics of an ideal linking framework within our setting. In the context of electricity sector modeling, for example, the soft iterative linkage and sequential calibration techniques are impractical because the main power sector model upon which the EPA relies, IPM, is proprietary as well as computationally and resource intensive. Even if it were possible to iteratively link the models, the proprietary nature of the sector model would limit reproducibility of the CGE modeling results. The traditional summary approach could be possible but presents challenges in this context as well. First, the policy levers available in the SAGE model (and most CGE models) often do not mimic those in a highly detailed bottom-up sector model. Therefore, should a regulation have compliance requirements that are not currently captured in SAGE explicitly (e.g. emission rate limits on certain types of electricity generators), the quality of the analysis could suffer. Second, summarizing behavioral responses from the detailed sector model in a CGE model may be complicated if the sector model captures only a portion of the expected behavioral responses in a general equilibrium framework (e.g., calibrating a CGE model with summary parameters that assumes fixed final demand). And third, such a technique would implicitly yield a different PE solution than what is determined by the detailed sector model alone, raising questions about which results are the authoritative PE estimates. Finally, the size and level of detail often reflected in a sector model makes it difficult to embed directly into a CGE model.

Another potential option for linking models, and technically the simplest but not discussed in SAB (2017), is to fix prices, quantities, or expenditures in the CGE model to correspond with the solution of the sector model and assume that feedback effects between the regulated sector and the rest of the economy are negligible. Unfortunately, it is unrealistic, especially with larger rules in sectors with many upstream and downstream linkages, to expect the GE outcome to match the PE solution (Delzeit et al., 2020). For instance, IPM minimizes the cost of achieving a fixed level of demand for electricity, and the price and quantity changes produced by IPM are reflective of this constraint. However, the GE model endogenizes electricity demand, suggesting the assumption of minimal feedbacks on the power sector is unlikely to be met. The CGE model also projects changes in factor and other input prices, which can have feedback effects on the GE solution for the electricity sector. There are also often many structural and accounting differences between a CGE and detailed sector model that may limit the ability of directly assuming the percent change in prices and/or quantities of one model adequately captures the compliance behavior in another model. For instance, if baselines are not identical, imposing the percent change in prices or quantities from one model in another will introduce measurement error, leading to inconsistencies across models.

3.2 A Hybrid Linkage

Given the limitations of traditional linking frameworks within our context, we develop a one-way hybrid linkage approach that combines elements of both the soft-linkage and summary function approaches. In our approach, we calibrate SAGE model inputs by targeting the PE incremental costs that would typically be generated by a detailed sector model such as IPM in a corresponding PE sub-model of SAGE (henceforth called SAGE-PE). SAGE-PE is designed to mimic, as much as possible, the detailed sector model. By relying on *incremental costs*, we can be agnostic about differences in structural behavior and accounting for prices and quantities between the sector model and SAGE-PE by targeting an equivalent *difference* between the baseline and policy cases. This approach provides a novel methodology for imposing the solution of the sector model within a CGE model without forcing the general and partial equilibrium results to be equivalent. Similar to the soft-linked approach, care is given in translating the model outputs to use as inputs into another model so that the two models are adequately capturing equivalent economic behavior. Similar to the typical way the summary function approach is used, elements of one model are used to calibrate another model that avoids the structural and accounting issues associated with the soft-linked framework. While we don't recalibrate SAGE model behavior to, say, specifically model generator technologies or target implicit elasticities similar to previous research efforts, we do calibrate the *inputs* to the SAGE model such that the implicit PE solution is consistent with the *outputs* of the sector model.

Figure 1: Hybrid SAGE Linkage Schematic

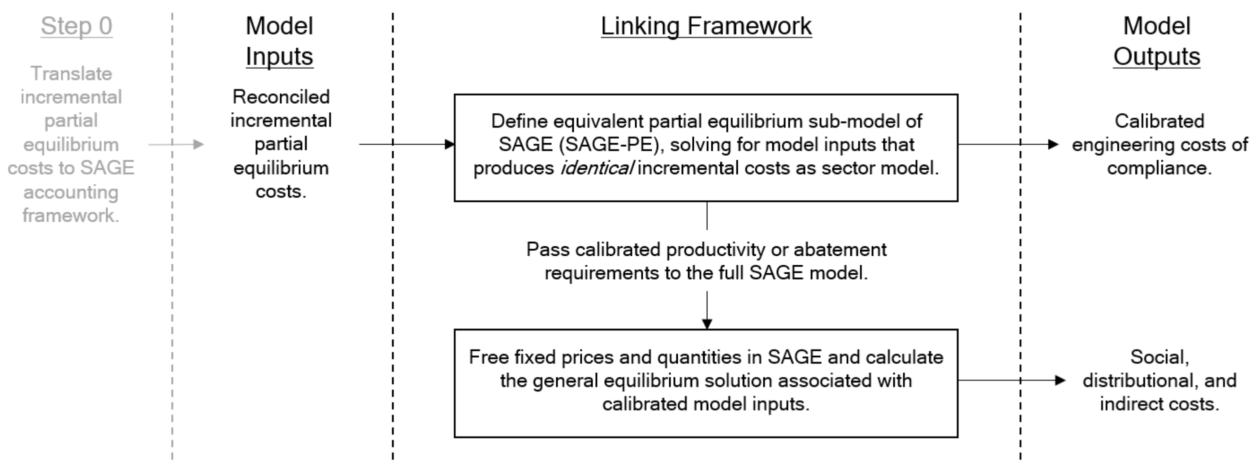


Figure 1 presents an overview schematic of the approach. The initial step (characterized as *Step 0*) reconciles differences in model structure and accounting by translating incremental costs from the detailed sector model to a format consistent with the SAGE framework. This includes aligning model years, distributing sector costs to SAGE model inputs (by fuel, other materials, labor, and capital), attributing costs to production vintages, and removing transfer payments that may be important to capture firm investment behavior in the PE sector model but inappropriate in SAGE due to potentially mischaracterizing resource use in the economy and double counting tax burdens in instances where SAGE levies taxes on inputs. We pass the reconciled incremental costs to SAGE-PE, a PE representation of the regulated sector (and potentially other related markets) as defined in SAGE that mimics the PE behavior and components of the sector model as close as possible. While SAGE-PE does not have the technology-rich detail of a sector model, it does capture aggregate endogenous responses in sectoral prices, input requirements, trade, and asset value of existing capital resources.

Because SAGE-PE is defined as a sub-model of SAGE, most model equations are described at length in Marten et al. (2023). The specific equations used in SAGE-PE depend on the structure of the PE sector model. Generally, the subset of SAGE equations and variables that could comprise SAGE-PE includes *conditional* profit-maximizing production behavior, sub-national and limited foreign trade, and market-clearing conditions that equate supply and demand in commodity markets.[5] As in SAGE, SAGE-PE models optimal behavior through a series of equilibrium conditions (formulated as a mixed complementarity problem). Production is characterized through zero profit conditions that require unit costs to be greater than or equal to unit revenues. If this condition is binding, then production is non-negative. There are two types of zero profit conditions in SAGE-PE. The first is for production of output in the regulated sector (and potentially, upstream or downstream sectors to the extent that they are included in the sector model), and the second operationalizes the Armington trade assumption that both allocates commodity outputs to regional markets (within region, the rest of the country, or international, to the extent that trade is endogenous in the sector model) and defines preferences for use of regionally-differentiated goods (Armington, 1969). Market-clearing conditions that equate supply and demand determine prices.

4 Stylized Example in the Electricity Sector

We illustrate the hybrid linkage approach with a stylized regulation in the electricity sector using assumed incremental PE costs similar to the types of outputs from a power sector model like IPM. We assume that the power sector model characterizes the supply-side of the electricity sector while also modeling some upstream equilibrium impacts in primary energy sectors (coal, natural gas, and refined oil). Like IPM, we assume that the model is a linear program and solves for the least cost approach for complying with regulatory requirements with detailed information on control technologies while meeting fixed electricity demands (among other constraints). PE compliance costs attributed to an environmental regulation are calculated as the *increment* between the cost of meeting the fixed electricity demand in the baseline and policy scenarios, which includes the costs of compliance technologies, changes in the composition of electricity generation, and changes in energy prices and quantities. Finally, we assume that it is not possible to iteratively link the power sector model with SAGE.[6]

A detailed PE model of the electricity sector, like IPM, produces detailed expenditure information and emissions outputs by model plant, which includes aggregate representations of unit-level information for existing generators and characterizations of new or retrofit/retire options, along with electricity price impacts by region.[7] This detailed information is important for quantifying the sectoral

[5]Equations are conditional on fixed prices not considered by the sector model.

[6]For instance, as in the case of IPM, which is owned and operated by ICF. See `https://www.icf.com/technology/ipm` for more on IPM. For technical details of IPM, see the model's documentation, available at: `https://www.epa.gov/power-sector-modeling/documentation-post-ira-2022-reference-case`, or EPA's most recent peer review of the modeling framework and associated base case (Burtraw et al., 2020).

[7]It is important to note that the distinction between extant and new capital in an economy-wide framework like SAGE is not the same thing as differentiating existing and new generation in a power sector model. An existing generation unit in a power sector model can typically extend its lifespan through additional investments and may comply with environmental or other regulations through retrofit investments. As such, an existing generation unit in a power sector model is often a combination of new and extant capital, as the focus of vintaging in the modeling framework is on the construction date

compliance behavior expected in response to a rulemaking. However, to link a power sector model like IPM to an economy-wide model such as SAGE, we need the change in aggregate sectoral expenditures by commodity or factor.[8] This requires a translation of the expenditure information along financial categories produced as output from the sector model into commodity and factor expenditures used by the economy-wide model. For this exercise, key model output costs include capital costs, fuel costs, and fixed and variable operations and maintenance costs. Capital costs can be reported both as 1) overnight capital costs, which are the total cost of capital in the time period it is installed assuming no interest payments, or 2) capital flow payments, which are amortized payments spread over the lifetime of the capital. Costs are further denominated by region and generator vintage.

4.1 Defining SAGE-PE

In this setting, SAGE-PE is designed to treat market outcomes in sectors other than electricity and primary energies, final electricity demand, changes in factor prices, and constraints on factor supply as exogenous.[9] Throughout this section, we use overbar notation to indicate baseline values (and also those exogenous values that are fixed to their baseline levels). Let p^y_{trs} denote the output price for sector s in time t and region r, and let p^a_{trg} denote the end use price of commodity g (input prices). Let $\overline{p}^a_{trs'}$ denote fixed baseline input prices for goods not modeled in the power sector model (e.g., the price of services), $\overline{p}^l_{tr}$ the fixed price of labor, $\overline{r}^k_{tr}$ the fixed rental rate on use of *new* capital, and $r\_ex^k_{trs}$ the rental rate on *extant* capital. Notably, we maintain an endogenous rental rate on extant capital to model the changes in the shadow value on existing capital stock. The model includes productivity indices for production with extant capital ϕ^{ex}_{tr*s} and production with new capital ϕ_{tr*s}, where $*$ denotes inputs associated with the productivity index to allow for input-dependent productivity changes over time, regions, sectors, and production vintages. In the baseline, all productivity indices ($\overline{\phi}^{ex}_{tr*s}$ and $\overline{\phi}_{tr*s}$) are set to unity, with the exception of those assigned to labor inputs which reflect projections of sector-differentiated labor productivity. Using ZP to represent zero-profit, we model production of electricity and primary energies with new capital, Y_{trs}, and extant capital, Y^{ex}_{trs}, as:[10]

$$ZP^Y_{trs}(p^y_{trs}, p^a_{trg}|\overline{p}^l_{tr}, \overline{r}^k_{tr}, \overline{p}^a_{trs'}, \overline{\phi}_{tr*s}) \geq 0 \quad \perp \quad Y_{trs} \geq 0 \quad \forall \quad (s,g) \in \{ele, gas, coal, oil\} \qquad (1)$$

$$ZP^{Y^{ex}}_{trs}(p^y_{trs}, p^a_{trg}, r\_ex^k_{trs}|\overline{p}^l_{tr}, \overline{r}^k_{tr}, \overline{p}^a_{trs'}, \overline{\phi}^{ex}_{tr*s}) \geq 0 \quad \perp \quad Y^{ex}_{trs} \geq 0 \quad \forall \quad (s,g) \in \{ele, gas, coal, oil\} \qquad (2)$$

of the unit and not the vintage of the capital. In SAGE, existing capital stocks are assumed to depreciate over time, and their economic lifespan cannot be extended through investment. Unlike in a power sector model, the specific construct of a generation unit does not exist in the SAGE modeling framework.

[8]Marten et al. (2019) have shown that economy-wide impacts are dependent on the input intensities of compliance behavior in response to environmental regulation.

[9]Notably, while a power sector model, like IPM, may not model changes in final demand for electricity, we do allow SAGE-PE to adjust electricity output to satisfy reductions or increases in electricity input demands in the electricity sector and primary energy sectors.

[10]This mathematical representation of SAGE-PE glosses over many of the details of functional form assumptions found in the model code and described in Marten et al. (2023).

We modify SAGE-PE to include new capital demands in extant production for retrofits (hence the inclusion of $\bar{r}^k_{tr}$ in the conditional statement). Letting $kd^{ex}_{ex}(r\_ex^k_{trs}, Y^{ex}_{trs})$ denote extant capital demands in production using extant capital of good s in region r and time period t, we define the shadow value of extant capital by holding fixed the extant capital demands to baseline levels ($\overline{kd}^{ex}_{ex\,trs}$):[11]

$$\overline{kd}^{ex}_{ex\,trs} - kd^{ex}_{ex}(r\_ex^k_{trs}, Y^{ex}_{trs}) \geq 0 \quad \perp \quad r\_ex^k_{trs} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{3}$$

Two zero-profit conditions are used to characterize the allocation of sectoral output to and demand from regional markets.[12] Let p^d_{trs} denote the within-region price of good s in region r and time period t, p^n_{ts} denote the national price of good s in time period t, and $\overline{p^x_{ts}}$ denote the fixed price of exports for good s and time period t.[13] In this case, we characterize the output price through the zero-profit condition for the allocation of sector output:

$$ZP^e_{trs}(p^d_{trs}, p^n_{ts}, p^y_{trs}|\bar{p}^x_{tr}) \geq 0 \quad \perp \quad p^y_{trs} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{4}$$

The Armington aggregator A_{trs} characterizes the total quantity of goods demanded from regional trade markets for a given commodity in a time period and region. Letting $\bar{p}^m_{ts}$ denote a fixed price of imports, the aggregator is defined as:

$$ZP^m_{trs}(p^a_{trs}, p^n_{ts}, p^d_{trs}|\bar{p}^m_{tr}) \geq 0 \quad \perp \quad A_{trs} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{5}$$

The end use price for commodity s in region r and time period t is determined by equating the supply of the Armington aggregate with total demand as determined through the sum of intermediate inputs and final demand (held fixed in SAGE-PE and denoted as $\overline{fd}_{trs}$). Using MC for market clearance, we model the market as:

$$MC^a_{trs}(A_{trs}, Y_{trs}, Y^{ex}_{trs}|\overline{fd}_{trs}) \geq 0 \quad \perp \quad p^a_{trs} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{6}$$

Similarly for p^d_{trs} and p^n_{tr}, regional market prices are determined by equating supply with demand:

$$MC^d_{trs}(A_{trs}, Y_{trs}, Y^{ex}_{trs}) \geq 0 \quad \perp \quad p^d_{trs} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{7}$$

$$MC^n_{ts}(A_{trs}, Y_{trs}, Y^{ex}_{trs}) \geq 0 \quad \perp \quad p^n_{ts} \geq 0 \quad \forall \quad s \in \{ele, gas, coal, oil\} \tag{8}$$

One of the general ways to represent an environmental regulation in a CGE model is as a productiv-

[11] Input demands are differentiated between demands from production with extant capital (denoted with an *ex* superscript) and production with new capital (no superscript). Because production with extant capital demands both extant and new capital to account for retrofits of existing production, we differentiate capital demands with a subscript for either *ex* or *new*.

[12] SAGE and SAGE-PE do not model bilateral trade between U.S. regions. Rather, the models rely on a *pooled* national market that equates the total supply to regions outside of the region a good is produced in (but within the U.S.) to the demand from that same market.

[13] While the price of exports and imports are fixed, SAGE-PE captures imports of fuels and electricity as it relates to demands in the electricity sector.

ity shock. This can be interpreted as modeling compliance with the regulation by requiring more inputs (e.g., control technologies) to produce the same amount of output to comply with the regulation. In the SAGE and SAGE-PE models, this is implemented through augmenting the reference productivity indices denominated by input (materials, fuels, labor, and capital).[14] Our general approach for aligning SAGE with the power sector model is to *calibrate* changes to reference model productivity indices such that the incremental input costs in the SAGE-PE solution are consistent with the those determined by the sector model solution.

Suppose we have representative PE incremental costs from a power sector model, like IPM, in the electricity sector, indexed by set s, for existing and new builds for labor ($\widehat{ld\_ex}^{pe}_{trs}$, $\widehat{ld\_new}^{pe}_{trs}$), capital services ($\widehat{kd\_ex}^{pe}_{trs}$, $\widehat{kd\_new}^{pe}_{trs}$), and intermediate demands ($\widehat{id\_ex}^{pe}_{trgs}$, $\widehat{id\_new}^{pe}_{trgs}$, where we denote fuel commodities like coal, oil, and natural gas using g and other material inputs as s') denominated in 2016 dollars. We calibrate SAGE-PE inputs by linking endogenous productivity indices to constraints on incremental costs by input type through additional complementarity conditions. Denominating SAGE-PE input costs in 2016 dollars, we define the incremental SAGE-PE costs as the difference between the policy equilibrium and the baseline. The complementarity conditions allow the requisite productivity indices to adjust to equate SAGE-PE and sector model PE incremental costs. Because prices for factors and non-energy inputs are fixed, the SAGE-PE incremental input costs for factors and non-energy inputs are driven through quantity demand changes for labor ($ld^{ex}(Y^{ex}_{trs}|\bar{p}^l_{tr})$, $ld(Y_{trs}|\bar{p}^l_{tr})$), new capital ($kd^{ex}_{new}(Y^{ex}_{trs}|\bar{r}^k_{tr})$, $kd(Y_{trs}|\bar{r}^k_{tr})$), and material inputs ($id^{ex}(Y^{ex}_{trs}|\overline{pa}_{trs'})$, $id(Y_{trs}|\overline{pa}_{trs'})$). Incremental costs for electricity and primary-energy inputs, indexed by set g, incorporate both changes in prices (p^a_{trg}) as well as input demand quantities ($id^{ex}(p^a_{trg}, Y^{ex}_{trs})$, $id(p^a_{trg}, Y_{trs})$).

$$\overbrace{\bar{p}^l_{2016r}\, ld(Y_{trs}|\bar{p}^l_{tr})}^{\text{SAGE-PE Policy Input Cost}} - \overbrace{\bar{p}^l_{2016r}\,\overline{ld}_{trs}}^{\text{SAGE-PE Baseline Input Cost}} - \overbrace{\widehat{ld\_new}^{pe}_{trs}}^{\text{Incremental PE Input Cost}} \geq 0 \quad \perp \quad \overbrace{\phi_{tr'l's}}^{\text{Endogenous Productivity Index}} \geq 0 \tag{9}$$

$$\bar{r}^k_{2016r}\, kd(Y_{trs}|\bar{r}^k_{tr}) - \bar{r}^k_{2016r}\,\overline{kd}_{trs} - \widehat{kd\_new}^{pe}_{trs} \geq 0 \quad \perp \quad \phi_{tr'k's} \geq 0 \tag{10}$$

$$\bar{p}^a_{2016rs'}\, id(Y_{trs}|\bar{p}^a_{trs'}) - \bar{p}^a_{2016rs'}\,\overline{id}_{trs's} - \widehat{id\_new}^{pe}_{trs's} \geq 0 \quad \perp \quad \phi_{trs's} \geq 0 \tag{11}$$

$$p^a_{2016rg}\, id(p^a_{trg}, Y_{trs}) - \overline{p^a}_{2016rg}\,\overline{id}_{trgs} - \widehat{id\_new}^{pe}_{trgs} \geq 0 \quad \perp \quad \phi_{trgs} \geq 0 \tag{12}$$

$$\bar{p}^l_{2016r}\, ld^{ex}(Y^{ex}_{trs}|\bar{p}^l_{tr}) - \bar{p}^l_{2016r}\,\overline{ld}^{ex}_{trs} - \widehat{ld\_ex}^{pe}_{trs} \geq 0 \quad \perp \quad \phi^{ex}_{tr'l's} \geq 0 \tag{13}$$

$$\bar{r}^k_{2016r}\, kd^{ex}_{new}(Y^{ex}_{trs}|\bar{r}^k_{tr}) - \bar{r}^k_{2016r}\,\overline{kd}^{ex}_{new\,trs} - \widehat{kd\_ex}^{pe}_{trs} \geq 0 \quad \perp \quad \phi^{ex}_{tr'k's} \geq 0 \tag{14}$$

$$\bar{p}^a_{2016rs'}\, id^{ex}(Y^{ex}_{trs}|\bar{p}^a_{trs'}) - \bar{p}^a_{2016rs'}\,\overline{id}^{ex}_{trs's} - \widehat{id\_ex}^{pe}_{trs's} \geq 0 \quad \perp \quad \phi^{ex}_{trs's} \geq 0 \tag{15}$$

$$p^a_{2016rg}\, id^{ex}(p^a_{trg}, Y^{ex}_{trs}) - \bar{p}^a_{2016rg}\,\overline{id}^{ex}_{trgs} - \widehat{id\_ex}^{pe}_{trgs} \geq 0 \quad \perp \quad \phi^{ex}_{trgs} \geq 0 \tag{16}$$

We solve SAGE-PE with these additional constraints to uncover productivity parameters that

[14] One could also implement regulatory scenarios as abatement requirements in SAGE. However, using the productivity parameters, we can accommodate substitutability in the production functions that interacts with compliance requirements, which is not possible when using the abatement requirements methodology. For instance, using productivity indices would allow us to better capture situations where the regulation may require add-on controls on certain types of generators, which can cause a shift in generation to other types of generators.

produce an equivalent PE incremental cost as the power sector model. The adjusted productivity indices represent an implicit engineering cost of compliance not inclusive of the PE price and quantity changes. While SAGE cannot currently capture nuanced policy levers like emissions rates on certain types of generators like in detailed sectoral models, this calibration routine provides a means to translate detail-rich PE modeling results into a set of calibrated engineering costs that represent an equivalent set of compliance requirements in the two frameworks. Notably, while this procedure enforces identical incremental costs across models, it could be that the PE percent change in prices and quantities differ across models due to accounting and structural reasons. Relying on incremental costs allows us to avoid reconciling differences in the underlying structures and parameterizations of both the electricity sector and associated upstream primary energy markets across the two models. We test the potential importance of this feature of the linking framework in a later section.

After solving for the calibrated productivity indices, we then pass these to the full SAGE model to generate social cost, distributional, and indirect impacts of the modeled policy. We calculate social costs as total equivalent variation across regions and household types, or the sum of household willingness to pay to avoid the costs of the environmental policy.[15] This is estimated by calculating the needed additional income to make households as well off as in the policy equilibrium under baseline prices. Distributional outcomes, or impacts on heterogeneous households denominated by region and income level, can be assessed using the disaggregated equivalent variation estimates. We can also evaluate indirect costs as shifts in sectoral production and labor market outcomes.

4.2 Scenario Design

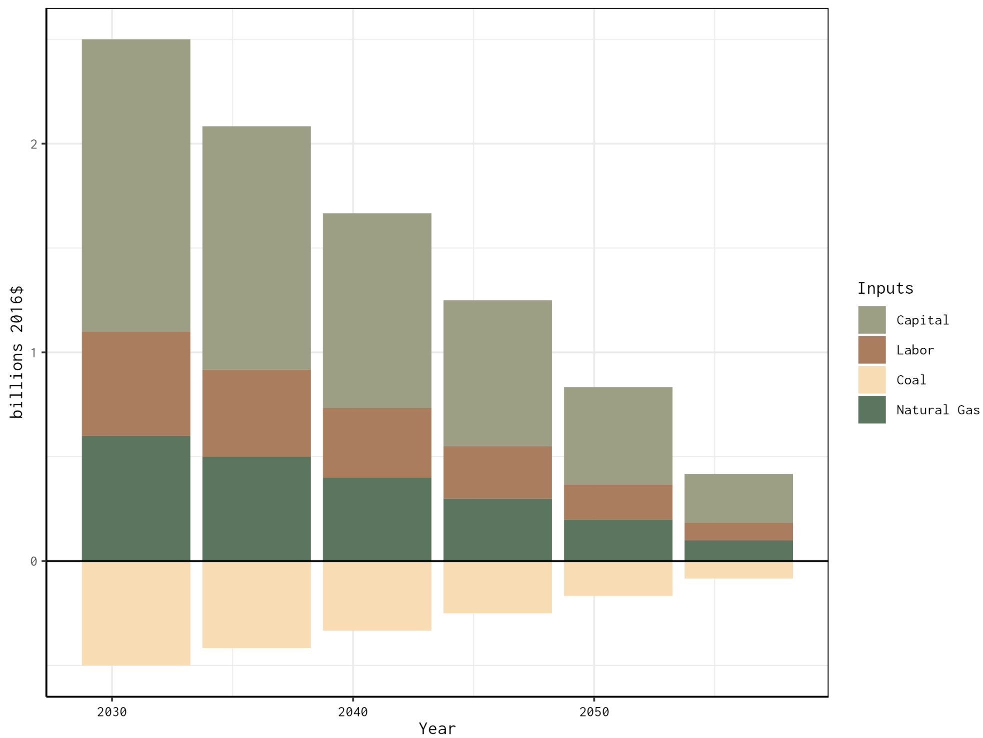
To demonstrate the hybrid linking method we consider an illustrative policy in the electricity sector. The goal is not to analyze a specific environmental regulation but to demonstrate the hybrid linking approach. Therefore, we construct an illustrative scenario that is within the general magnitude of recent power sector policies and that captures generalities common in the distribution of incremental costs in recent power sector policies. We assume that a power sector model has been used to analyze the illustrative environmental policy and found incremental costs associated with meeting a fixed electricity demand that peaks at $2 billion in 2031 and decline to zero by 2056, the assumed end of the PE model time horizon in this example. Declining costs over the model horizon are consistent with a future where there is an expansion of cleaner electricity production in the baseline that renders the illustrative policy non-binding in later model years. The present value of the incremental cost for the illustrative policy is $13.2 billion (2016$) with a corresponding annualized value of $0.6 billion.[16] The illustrative policy is designed to capture sector-wide compliance responses that reflect investment in pollution control retrofits at existing generation units along with a reduction in coal-fired generation and an increase in natural gas and renewable generation, including through increased investment in

[15]Note that SAGE does not include the potential benefits from environmental regulation in the form of improved environmental quality. Therefore the equivalent variation as computed by the model is defined as the social *costs* of the regulation.

[16]These calculations assume linear interpolation between model time steps and are discounted based on the SAGE internal discount rate of 0.045.

new generation sources. Figure 2 describes the distribution of illustrative incremental costs from the power sector model at the national level. We assume the incremental costs are distributed to regions based on their relative share of electricity generation in the baseline. One of the challenges in translating PE modeling outputs into SAGE model inputs is assigning costs to particular inputs. In our illustrative scenario, we assume that the aggregate incremental cost are composed of increases in the use of capital, labor, and natural gas and reductions in the use of coal.[17]

Figure 2: Illustrative Incremental Costs



The input composition of the illustrative policy in Figure 2 reflects *net* changes in the expenditure on inputs to produce a fixed quantity of electricity. A reduction in coal-fired generation is associated with a reduction in expenditures on coal use as well as capital, labor, and other inputs. Likewise, an increase in the use of natural gas generation and renewables is associated with increased expenditures on natural gas, capital, labor and other inputs. The aggregate changes in Figure 2 reflect a combination of those reductions and additions are assumed to be the net incremental costs of the illustrative policy. We base the input composition of the illustrative policy on Henry et al. (2023), a database called MEEDE (Micro-level Engineering, Environmental, Economic Detail of Electricity) Version 2 that characterizes the costs of generating electricity by input. For the sake of simplicity in this illustrative scenario, we assume away costs associated with variable operations and maintenance costs and assume that the input composition does not change across time. The composition of the assumed compliance pathway

[17] In cases where the power sector model deploys a technology that is inactive in the baseline but used in the policy scenario, it may be necessary to construct a cost structure for the technology if it is not easily mapped to a representative sector in the CGE model.

is reflective of cost shares by generation type in 2019 in addition to assumed additional labor needed for administrative and operational compliance requirements.[18]

The capital costs described in Figure 2 reflect aggregate annualized capital flow payments across existing and new generators. In order to disaggregate capital flow payments by generator vintage, we construct a mathematical program to simultaneously solve for changes in overnight capital costs and capital flow payments by generator vintage consistent with assumed values for the economic life (or the time it takes to pay off the capital investments inclusive of rates of return) of the installed capital and the average before tax weighted cost of capital (or interest rate on capital investments). Using values consistent with IPM, we assume retrofit capital on existing generators has an economic life of 15 years, new build capital has an economic life of 30 years, and the average weighted cost of capital is 3.76%.[19] We amortize the value of the incremental overnight capital costs by constructing a capital recovery factor (CRF) that differs by generator vintage, v:

$$crf_v = \frac{r}{1-(1+r)^{-l_v}} \tag{17}$$

where r is the weighted cost of capital, and l_v is the assumed economic life of the capital investment. The capital recovery factor represents the percentage of the change in the overnight capital costs that must be paid annually to recover the cost of the investment net interest payments (Bodansky, 2007; Morris et al., 2019; EPA, 2018). Using our reference assumptions, we find that the the CRF is 8.8% and 5.6% for existing and new capital investments, respectively. Figure 3 shows the calculated change in overnight capital costs where the largest change in overnight capital happens in 2031 due to relatively increased capital demands in 2031. As is common in many PE analyses of power sector regulations, the change in overnight capital is cyclical where negative numbers represent accelerated new builds and retirements.[20] Notably, we report changes in overnight capital costs as both a consistency check that the illustrative policy simulation aligns with the types of sector model outputs we may expect in real world setting as well as to treat the way capital payments are translated between the models in a sensitivity. In our main simulation, we assign capital payments assuming IPM values for interest rates and capital lifespan. Alternatively, we could align capital payments between models by targeting the change in overnight capital investments as the real resource use in the economy. This assumption

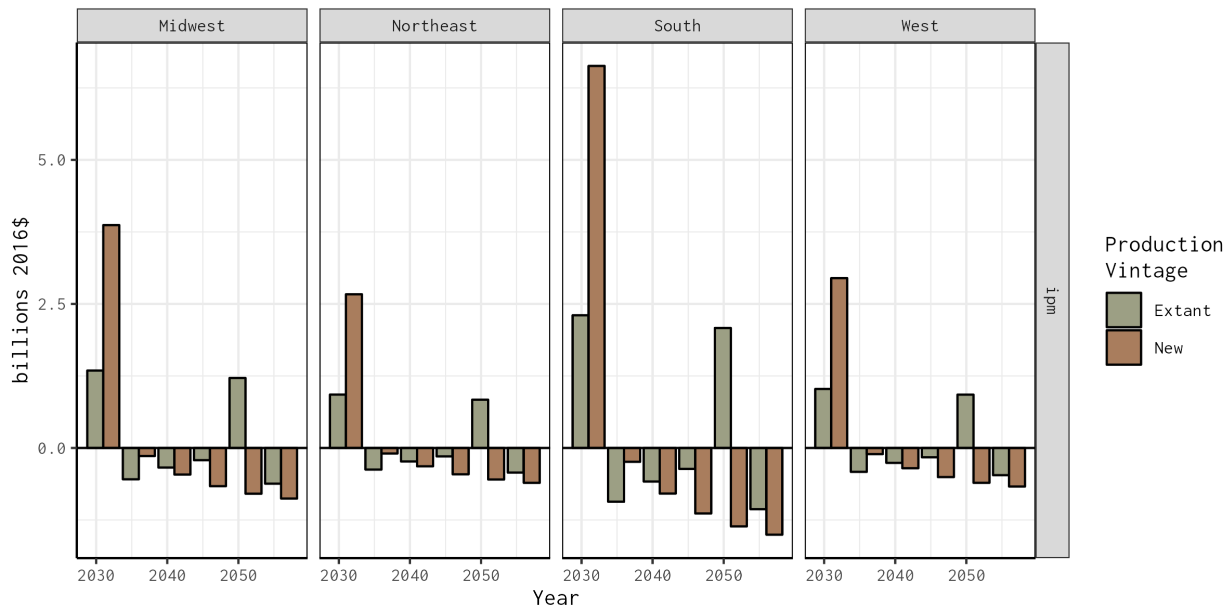
[18]Notably, in a real world application, power sector modeling results, like those from IPM, would provide information on input composition of the incremental costs of a rule. Here, we rely on cost information from Henry et al. (2023) to develop a meaningful but illustrative scenario. Specifically, we assume that 25% of the aggregate shock size is a reduction in coal use and rely on approximate costs shares reported by MEEDE Version 2 for coal generation (.45 fuel, .3 capital, and .25 labor), natural gas generation (.45 fuel, .4 capital, .15 labor), and for wind and solar generation (.8 capital, .2 labor) to characterize the net change in input use. We've attributed all of fixed operations and maintenance costs of generation to labor. Given a reduction in coal generation, we assume increased costs are split between natural gas generation and renewable generation and that a portion of the aggregate shock size is associated with additional labor requirements associated with the operation of controls and administrative responsibilities.

[19]These assumptions are approximately consistent with the EPA's Power Sector Modeling Platform Version 6, Post-IRA 2022 Reference Case. In reality, however, IPM incorporates a heterogeneous distribution of values for the weighted cost of capital and economic lifespan of capital investments that differ by unit type.

[20]For an example of this type of result, see the Regulatory Impact Analysis for the Good Neighbor Plan, at: `https://www.epa.gov/csapr/good-neighbor-plan-2015-ozone-naaqs`.

is treated in sensitivity in a later section. See Appendix A for more details of the creation of the illustrative policy.

Figure 3: Illustrative Incremental Overnight Capital Costs



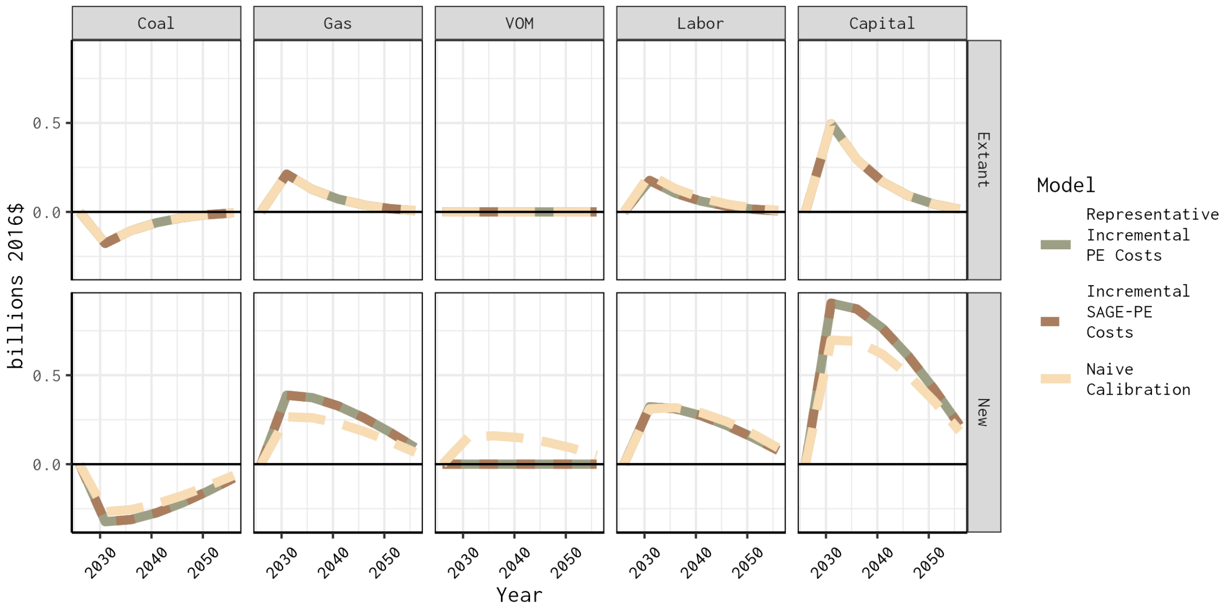
4.3 Calibration

The illustrative incremental costs are representative of PE costs estimates that would come from a power sector model and are inclusive of the costs of installing and operating pollution controls, fuel price changes, and costs associated with shifts in generating technologies. The linking framework aims to align SAGE-PE with the illustrative power sector model costs by solving for model inputs that reproduce identical incremental costs in the electricity sector, as described in Section 3.2. Figure 4 reports the outcome of the calibration procedure in the form of incremental costs by model input and capital vintage (represented as the difference in the value of inputs between the policy case and baseline). When the policy is introduced into the SAGE-PE framework using the calibration model inputs, SAGE-PE produces incremental costs in the electricity sector that are identical to illustrative results from the power sector model. Therefore, from a PE perspective, the SAGE-PE model captures equivalent compliance behavior in the electricity sector as measured by the incremental costs of the rule.[21]

To illustrate the value added of the linkage approach, Figure 4 also characterizes the partial equilibrium incremental costs from a naive calibration approach that assumes the PE cost estimates are not inclusive of price and quantity changes, eliminating substitution effects in the PE compliance

[21] As an additional robustness check on the calibration procedure that relies on additional model constraints (see Equations 9-16), we re-run SAGE-PE with the adjusted productivity parameters in a single iteration to verify that the reduced model is in equilibrium.

Figure 4: Calibration Verification, Incremental Costs by Input and Capital Vintage



behavior. The naive calibration approach leads to similar compliance behavior for costs levied on production with extant capital due to limited substitution possibilities in the production functions. However, the naive approach yields under-estimated incremental costs for capital and natural gas inputs and over-estimates for coal use, variable operations and maintenance (VOM) costs and labor in the electricity sector for production with new capital. These changes reflect differences in both output and price induced substitution effects relative to the hybrid linked approach. Changes in the electricity and energy prices induces substitution away from the more expensive inputs towards capital and labor (causing a non-zero cost in the "VOM" category). This leads to contractions in the amount of electricity the sector needs to produce for inputs into the electricity and energy markets. The naive approach does not account for these equilibrium effects.

The economics literature that has explored the difference between social costs developed with GE models and compliance cost estimates has typically compare social costs with engineering costs that are not inclusive of equilibrium impacts captured in a PE model (see Marten et al. (2019)). Therefore, it is useful to have a similar estimate of engineering costs from our illustrative policy to connect our work with the previous literature. Fortunately, the augmented productivity indices that are solved for in the calibration procedure represent a measure of the engineering costs of compliance as they are not inclusive of any equilibrium fuel price and substitution effects. For the illustrative scenario the present value of the engineering compliance costs are $14.1 billion (2016$) with an annualized cost of $0.6 billion (assuming a discount rate consistent with SAGE). Notably, these estimates are roughly 7% larger than the assumed PE incremental costs for the illustrative policy. The direction of this difference is as expected, since the PE incremental costs reflect the ability of the sector to minimize the costs of compliance through substitution possibilities not present in the engineering cost estimates

Table 2: Social, Incremental PE, and Engineering Compliance Cost Estimates (billions 2016$)

SAGE Model Years	Incremental PE Costs	Engineering Compliance Costs	GE Social Costs
2026	0	0	0.71
2031	2	2.20	0.79
2036	1.67	1.78	0.85
2041	1.33	1.40	0.92
2046	1.00	1.04	0.99
2051	0.67	0.68	1.07
2056	0.33	0.34	1.16
Present Value	13.18	14.12	17.01
Equivalent Annualized Costs	0.59	0.64	0.77

Notes: Social costs are calculated as equivalent variation. Present values and annualized cost estimates are calculated by interpolating between model years, assuming an infinite horizon, and are based on the internal discount rate in SAGE of 4.5 percent.

that do not include market responses.

4.4 Main Simulations

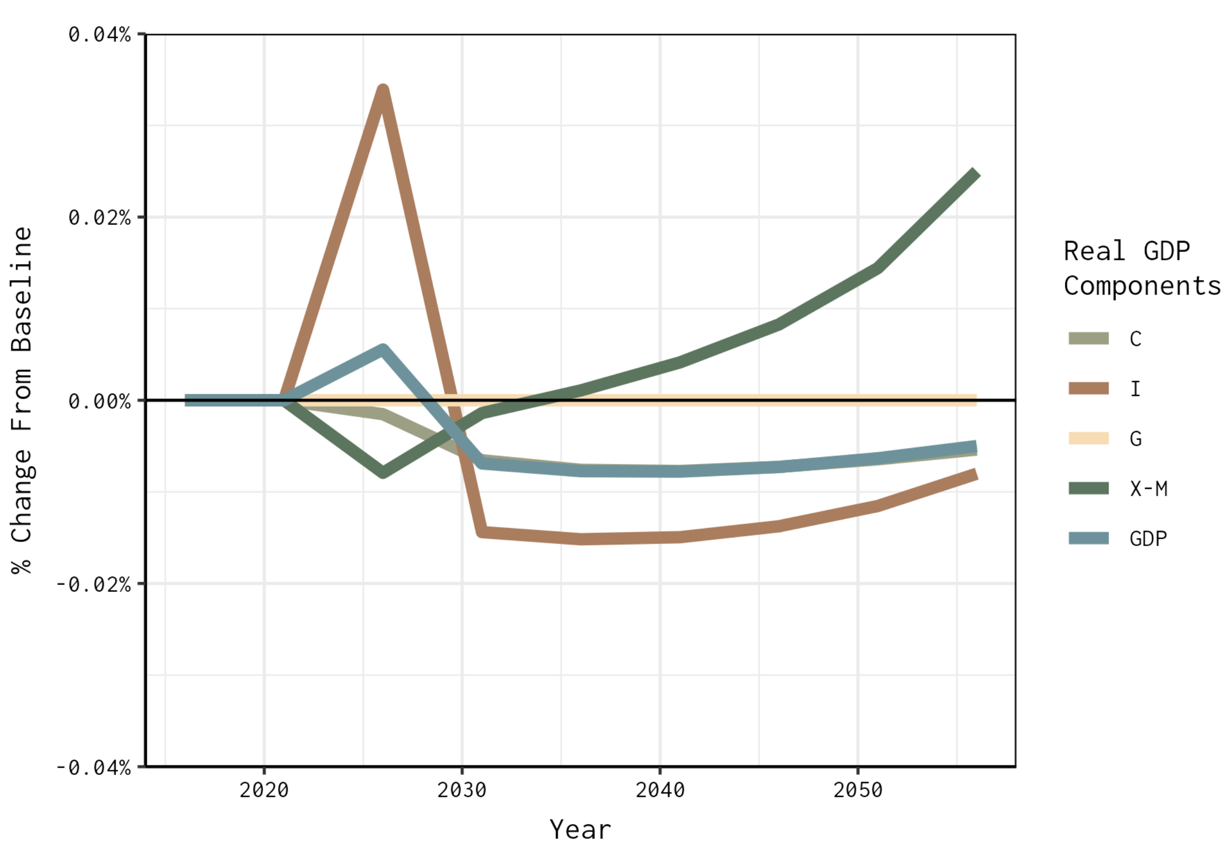
Table 2 presents the economy-wide, SAGE-GE social costs from the illustrative policy calculated as equivalent variation both within model years and aggregated assuming an infinite horizon. To help differentiate GE and PE modeling results, we label the full SAGE model results as SAGE-GE in subsequent figures. For comparison, Table 2 also presents the illustrative SAGE-PE compliance costs and the imputed engineering costs of compliance from the calibration procedure. In this stylized setting, we find that the social costs of the illustrative policy are approximately 21% greater than the imputed engineering compliance costs and 29% greater than the incremental PE costs. The relative size of social costs to engineering compliance costs roughly aligns with the findings of Marten et al. (2019), which generally find differences of 20% to 30% for policies imposed in the electricity sector depending on the policy and model specification.[22]

The GE social costs differ from the PE costs and engineering costs of compliance for several reasons. First, the GE costs reflect demand responses for electricity and energy inputs as the economy (inclusive of firms and households) responds to the impacts of the illustrative policy. As the price for electricity changes, demand for the relatively more expensive commodity also shifts. Second, the GE costs account for interactions with pre-existing distortions in the economy, mainly taxes and subsidies.

[22]We limit cost comparisons in this section to outcomes of the SAGE-GE and SAGE-PE frameworks. However, running the SAGE-GE model assuming the naive calibration approach yields an under-estimate of aggregate social costs by 0.5%. While the bias in overall social costs induced from the naive calibration may be small in this particular example with offsetting costs, it is heavily dependent on the input requirements of the shock due to differential interactions with pre-existing distortions across the economy. Furthermore, alternative partial equilibrium compliance behavior from the naive approach affects incidence of the illustrative shock, yielding different sectoral and distributional costs relative to the linked approach.

The "tax-interaction effect" has been shown to be a major driver in the divergence of partial and general equilibrium costs estimates. Goulder and Williams III (2003) find that a small change in labor supply induced by a policy can have a large tax interaction effect given that preexisting distortions in the labor market are large. This impact is not captured by a PE model limited to analyzing impacts on the regulated sector and closely related sectors. Further, Marten et al. (2019) find that, regardless of the input composition of an environmental regulation on the electricity sector, a model with a robust accounting of labor, capital, and output taxes produce social costs at least 15-20% larger than a model without taxes. Third, the GE costs also account for effects of reallocation, potential reductions in aggregate investment, and the resulting effects on economic growth. Finally, we note that while the PE compliance costs peak in the 2031 SAGE model year, aggregate social costs are spread out more evenly over the model time horizon as the economy smooths out the impact. Sectoral output can be reduced or increased depending on changes to relative prices and impacts can be ameliorated through trade.

Figure 5: % Change in Real GDP and Components



The estimated percent change from the baseline in real gross domestic product (GDP), or the real value of the goods and services produced by the U.S. economy, and its components (from the expenditure side) are presented in Figure 5. GDP is defined as the sum of the value (price times quantity) of all market goods and services produced in the economy and is equal to Consumption (C) + Investment (I) + Government (G) + (Exports (X) – Imports (M)). The illustrative policy leads to an increase in GDP in 2026 and subsequent decreases through the end of the model horizon. Compliance requirements accelerate investments in the electricity sector, leading to a net increase in aggregate investment in 2026 to augment the capital stock for compliance with the rule by 2031.[23] Increased investment reallocates resources away from consumption, which falls. Aggregate investment is expected to fall in later model years, as is consumption, reflecting the general contraction in the economy as resources are allocated towards pollution reduction in the electricity sector and away from other productive uses. The net trade balance is expected to show modest declines in the initial years as relative prices change domestically due to compliance with the illustrative policy, shifting some purchases towards imports, though the effect dissipates. Notably, GDP is a measure of economic output and not a measure of social welfare and therefore, the expected social cost of a regulation will generally not be the same as the expected change in GDP (EPA, 2015; SAB, 2017).[24]

Relative to a PE framework, SAGE endogenously models production for every sector in the economy. The GE changes to production are inclusive of how changes in the prices for electricity and primary energy inputs shift demand for inputs and factors across sectors in the economy. Furthermore, because the SAGE model endogenizes final demand, savings, and labor supply decisions, output (and input) changes are further differentiated from PE estimates. To demonstrate the sectoral impacts from the illustrative policy scenario across the model variants, we present the change in the quantity of national output and labor demand by sector in Figures 6 - 8.[25]

Figure 6 presents the percent change in national output and labor demand for the electricity, coal mining, and natural gas extraction and distribution sectors in 2031 for both SAGE-GE and SAGE-PE.[26] As expected, the largest changes, denominated in percent change from the baseline, are concentrated in these sectors. Relative to the SAGE-PE results, SAGE-GE estimates a larger decline in electricity output due to the demand side response endogenized in the model. The increase in labor demand across both SAGE-GE and SAGE-PE is indicative of the compliance requirements of the illustrative

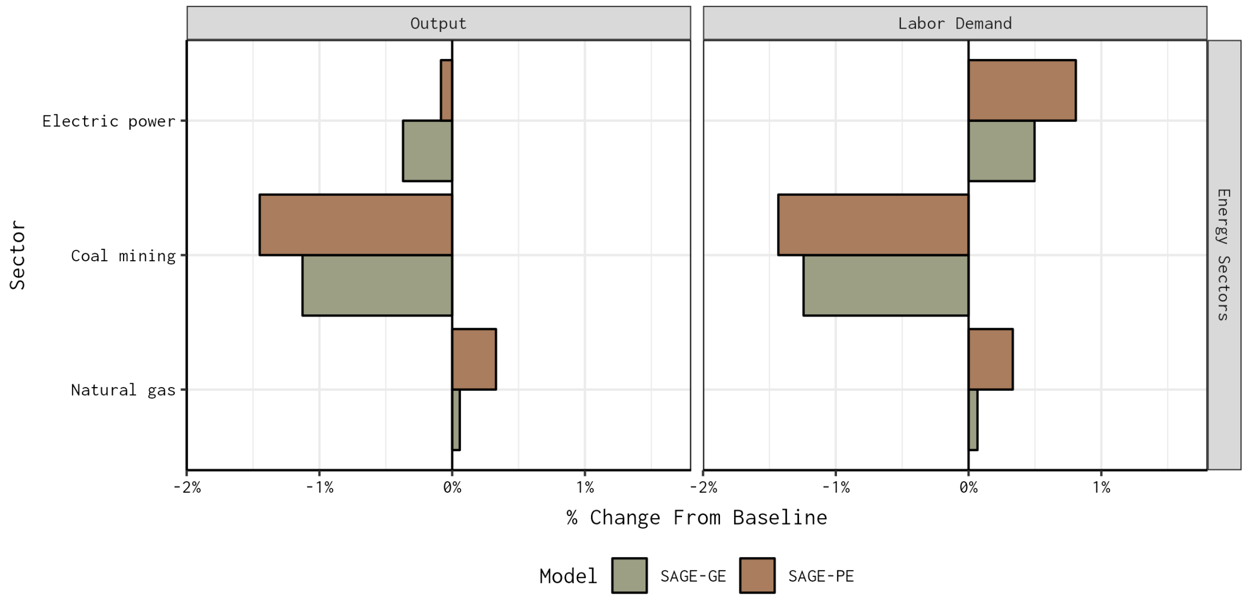
[23]In SAGE, the capital stock is augmented through investments made in the preceding model time period.

[24]The non-market benefits associated with pollution reduction are also not captured within measures of GDP,such that changes in GDP are not a valid measure of the net welfare effects of environmental policy.

[25]Notably, as with many other CGE models, SAGE assumes an economy with full employment, meaning that the labor market in the model adjusts to the new equilibrium such that there is no involuntary unemployment (i.e., all workers that want to work at the new prevailing wage can find a job). Any net changes in employment levels are associated with voluntary changes in labor. SAGE is therefore best suited to analyzing medium to long run changes in the expected use of labor across sectors in response to a policy change. While the model does not capture any near-term transition dynamics in the labor market, recent economics research suggests that they likely are a small component of overall welfare costs. Using a one-sector growth model, Rogerson (2015) finds that explicitly accounting for labor market transitions to a new equilibrium has a minimal impact on the aggregate welfare changes associated with new policies, though the author notes that this may be a function of the transition dynamics assumed in the model. Slower transition dynamics may increase their impact on social cost measures. Hafstead and Williams III (2018) develop a two-sector CGE model that incorporates several wage-setting mechanisms where the adjustment costs from transitioning between unemployment and employment are realized at much smaller time steps than are typical in a CGE framework. The authors estimate that the net employment impacts of environmental policy are small due to the offsets in the labor demanded by unregulated sectors.

[26]We report results for a single model year because the input composition and regional incidence of the illustrative policy is held constant across time. Therefore, the heterogeneity of impacts across sectors is also largely consistent across time, other than a scale effect as the magnitude of shock tends toward zero. Reporting impacts for additional years would be informative when the estimated PE compliance costs exhibit heterogeneity across time and regions.

Figure 6: % Change in Sectoral Output and Labor Demand in 2031 (Electricity, Coal, Natural Gas)

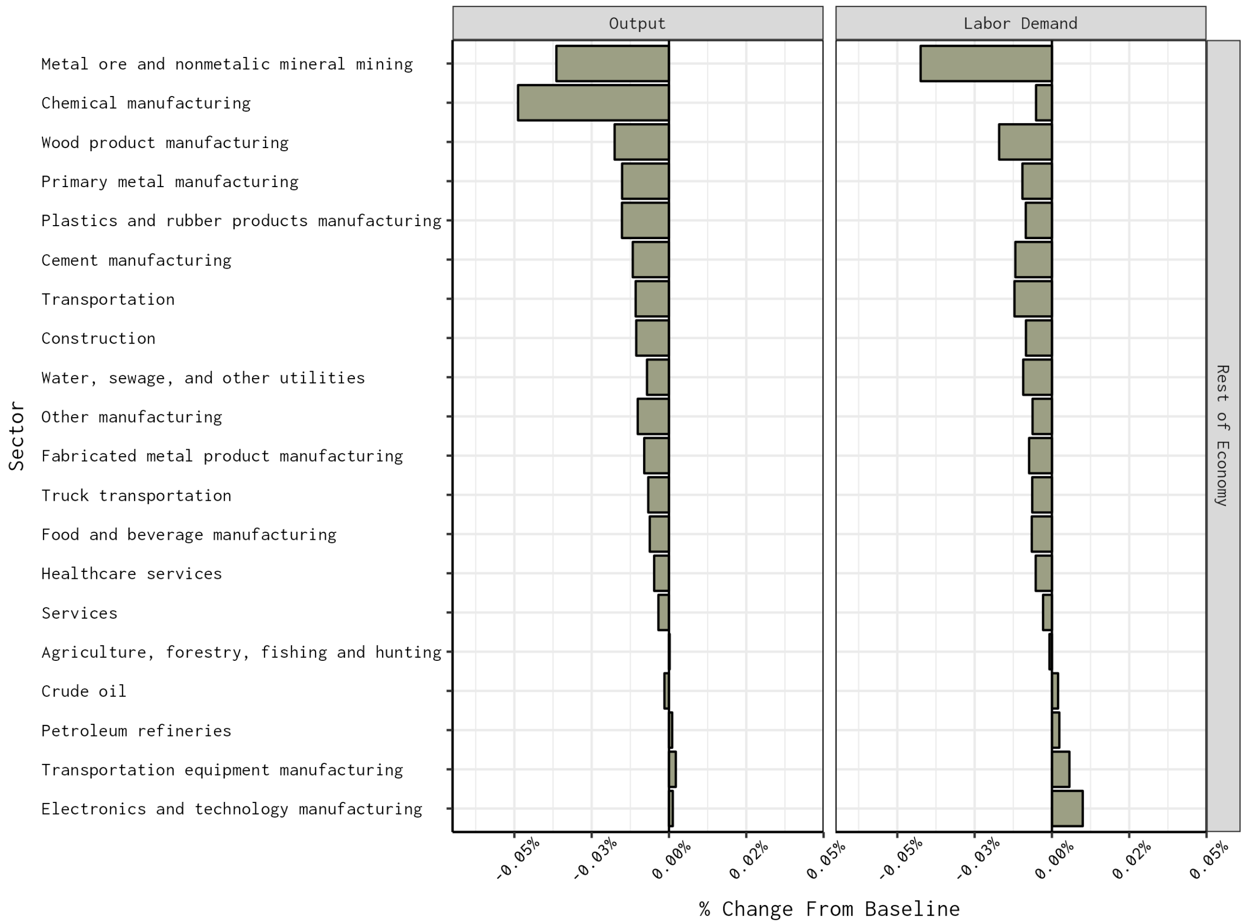


policy. Output in the coal mining sector is expected to decline across both model variants due to the reduction in coal use in the electricity sector. The reduction in coal mining output is larger in the SAGE-PE model because of the limited market responses captured in the PE model. Changes in factor prices and other inputs reduce the price of coal relative to other goods in the GE framework leading to slightly smaller shift away from coal use in the sector in addition to changes in exports. Finally, natural gas output is estimated to increase, though relatively less so in SAGE-GE due to both the reduced output in the electricity sector and reductions in demand elsewhere in the economy from rising prices. The percent change in labor demands tracks closely to output changes in the coal mining and natural gas sectors suggesting that the output effect (rather than the substitution effect) is the main driver for the impact.

Sectoral output and labor demand impacts in the rest of the economy in 2031 are reported in Figure 7. We report results only for the SAGE-GE model because changes to output and labor demand in the rest of the economy is exogenous in SAGE-PE.[27] In terms of percent change from the baseline, output and labor demand changes outside of the energy sectors directly affected by the illustrative policy are relatively smaller than impacts in the electricity sector and upstream fuel markets (if represented in *absolute* differences, the distribution would shift toward changes in larger sectors like services). Modest output and labor demand reductions are estimated in some relatively more energy intensive sectors (e.g., chemical, wood products, primary metal manufacturing) and those that support coal use in the electricity sector (e.g., transportation, non-metallic mineral mining) whereas output and labor demand

[27] Like IPM, SAGE-PE endogenizes the use of refined petroleum in the electricity sector and allows for limited upstream impacts in the sector. However, the illustrative policy considered in this paper assumes no incremental costs from the input and as a result, output and labor demand impacts from this sector are small (e.g., a 0.001% increase in output in the SAGE-GE model and a -0.005% reduction in output in the SAGE-PE model).

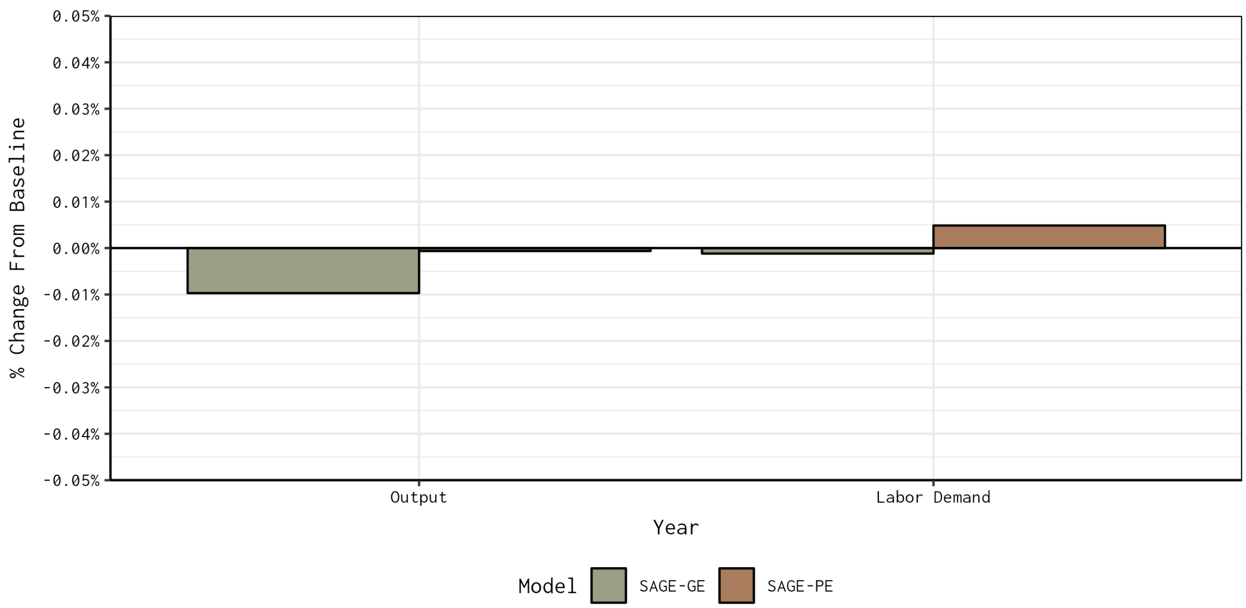
Figure 7: % Change in Sectoral Output and Labor Demand in 2031 (Rest of Economy)



increase slightly in sectors associated with capital formation to support investments needed to comply with the illustrative policy.

Combining output impacts across all sectors in the economy, Figure 8 presents the estimated net economy-wide percent changes in output and labor demand in 2031 across both SAGE-GE and SAGE-PE. Aggregate output and labor demand changes are small for the illustrative policy. Aggregate U.S. production is expected to decline in both model variants in 2031. In SAGE-PE, the reductions in output in the electricity sector and coal mining outweigh the increase in output in the natural gas sector. Similarly, reductions in output in SAGE-GE in the electricity sector, primary energy sectors, and energy-intensive sectors slightly outweigh output increases elsewhere in the economy. SAGE-GE output changes are larger than SAGE-PE output changes as they also include shifts elsewhere in the economy. Positive changes in aggregate labor demand in the SAGE-PE framework reflect increased labor demand associated with the compliance pathway in the electricity sector and increases in the natural gas sector outweigh reductions in the coal mining sector. Notably, in this PE framework, labor supply is assumed to be perfectly elastic. In the GE framework, the SAGE model assumes full employment, meaning that the model does not capture changes to *involuntary* unemployment and

Figure 8: % Change in Economy-wide Output and Labor Demand in 2031 (All Sectors)

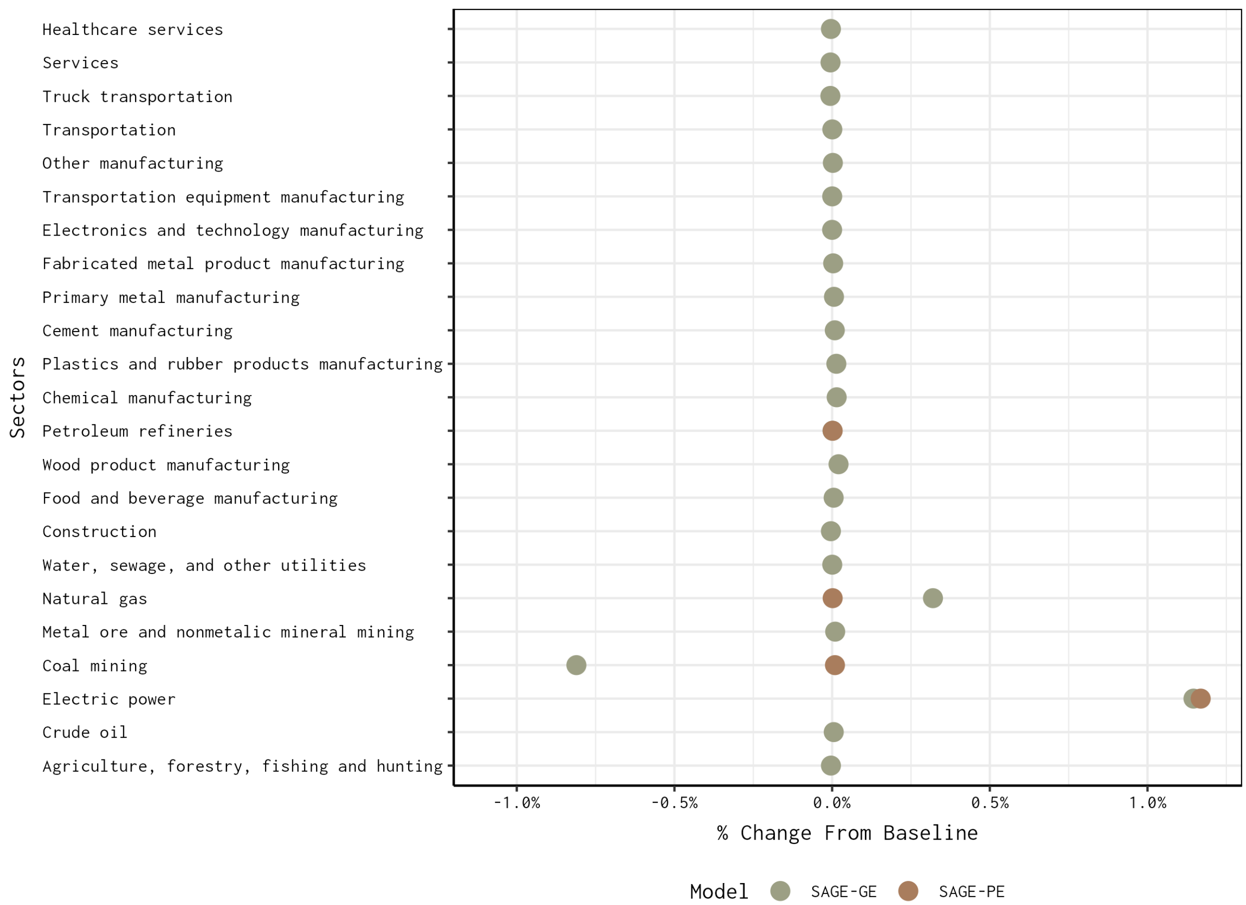


labor generally reallocates to sectors within a model region where it is most productive. The small net change in aggregate U.S. labor demand reflects a very small shift by households out of the labor market due to small decreases in the real wage rate.

Figure 9 presents the percent changes in real output prices for each sector in the SAGE model in 2031. CGE models report prices in relative terms.[28] Here, we denominate output prices in terms of the consumer price index (CPI) internal to the SAGE model, which reflects the overall change in end-use prices for the bundle of goods demanded by households. Characterizing prices relative to the CPI allows a comparison of changes in the magnitude of output prices to overall trends in the economy (i.e., a percentage change that is positive reflects a price that increases more than the average price changes across the economy). The largest percent changes in real output prices occur in the natural gas, electricity, and coal sectors. In SAGE-GE, the estimated natural gas price change is due to the net effect of both increased demand in the electricity sector as well as reductions in demand elsewhere in the economy as the price increases. The estimated change in the electricity sector output price reflects the additional costs associated with complying with the illustrative policy as well as demand side reductions in electricity use from both firms and households. Estimated price decreases for coal largely reflect the reduced demand for the fuel in the electricity sector. Notably, the SAGE-PE price impacts in the electricity sector are similar to those estimated by the full GE framework. SAGE-PE is less price sensitive in energy markets due to limited price responsiveness for inputs and factors in the

[28] SAGE solves for a set of relative prices through the selection of a numeraire, or a chosen price level used to denominate other prices in the model. In solving the default model, price changes are characterized relative to the foreign exchange rate in the initial period. A numeraire is required in this class of economic models to satisfy Walras' Law. A competitive GE model is homogeneous of degree one in prices, meaning that the equilibrium level price vector scaled by a common factor is also a solution to the model. This indeterminacy is solved, without loss of generality, by fixing a single price to align the number of equations and variables in the model.

Figure 9: % Change in Real Output Prices in 2031

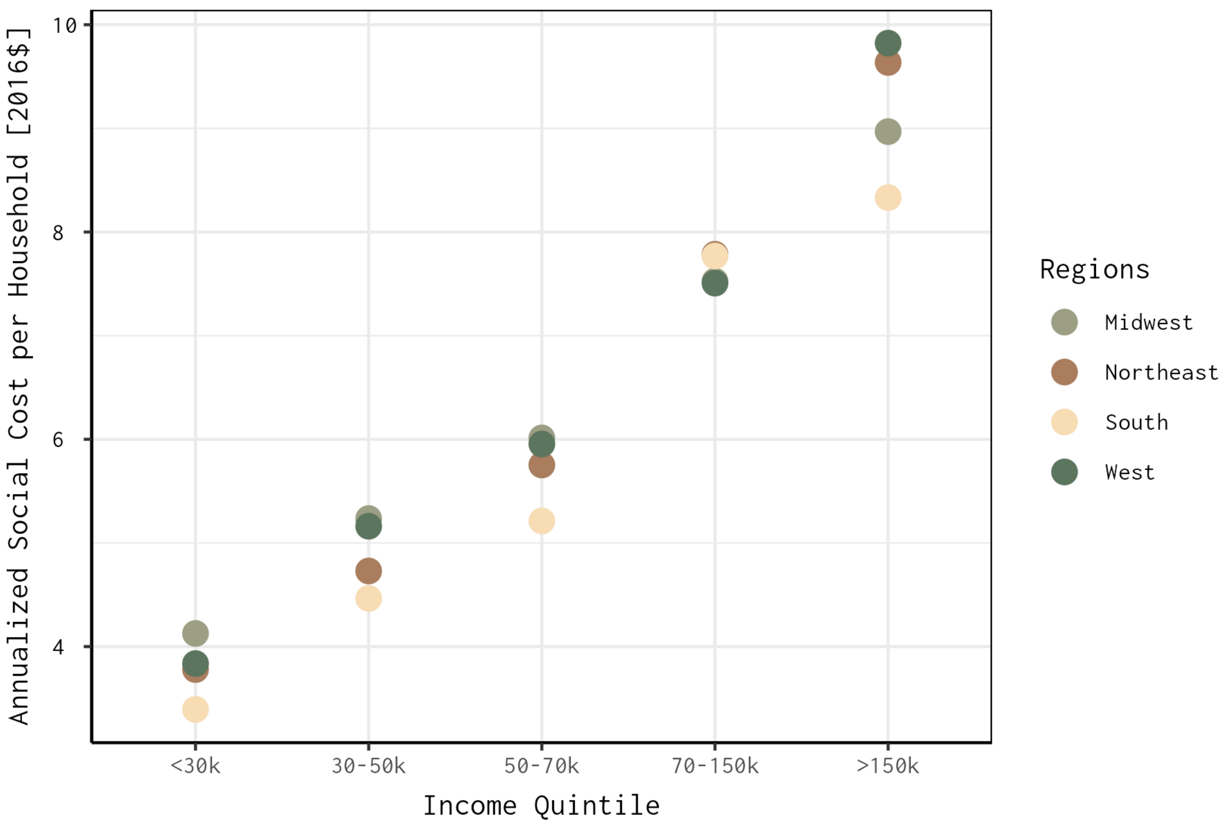


cost of production.

The social costs of a policy are ultimately borne by households. The linked framework affords us the ability to capture both source side (changes in labor, capital, and resource income) and use side (through changes in final goods prices) impacts of the illustrative policy on household welfare.[29] SAGE models representative households by approximate income quintiles in each of the four Census regions. This allows the social costs to be separately estimated across the income distribution and for different regions of the country, presented in Figure 10 as annualized social costs per household. Household costs are calculated by dividing the aggregate annualized social cost calculated for a given region-income quintile pairing by the total number of households in that region-income quintile pairing based on estimates from the Census' Current Population Survey for the benchmark year of the model. In this illustrative exercise, we find that social costs increase with income. The illustrative policy is estimated to cost households in the bottom income quintile roughly $4 a year into perpetuity and households in

[29] The ability to capture both income effects and changes in expenditure patterns may provide a more comprehensive assessment of household incidence over efforts that map modeled changes in the price for electricity to consumer expenditure data. However, the GE model is an aggregate representation of the economy, so any impacts that are more localized than what the model is able to capture may be missed.

Figure 10: Distribution of Annualized Social Costs per Household (2016$)



the top income quintile $9 a year into perpetuity. However, when characterizing social costs by region and income group as a percentage of full consumption (consumption of commodities plus leisure), the distribution of social costs flattens. There are several effects happening simultaneously that affect the distributional social costs. Low income households are relatively more burdened by the increase in electricity and natural gas prices since they tend to have higher expenditure shares on energy. Higher income households have relatively small expenditure shares on energy and are therefore less burdened by the price increases on those commodities, but they face additional burdens due to changes in the returns to their capital investments and resource holdings.

4.4.1 Sensitivity: Accounting for Capital Payments

Aligning CGE and detailed sector models can be complicated by differences in how each model accounts for capital payments. CGE models, like SAGE, account for capital as a cumulatively depreciated asset that represents the aggregate physical capital stock in the U.S., whereas a detailed PE model, such as IPM, tends to define capital more specifically with heterogeneous lifespans and costs by technology. The models can be aligned by either targeting incremental overnight capital costs (e.g., the magnitude and timing of the resource change) or through targeting capital flow payments. The main simulations above adopt the latter approach. Because the representation of capital is different between the models, calibrating the frameworks to produce consistent changes in PE capital flow payments will lead to differences in the implied capital stock changes required. However, this difference may be viewed as a translation of payments, or rather a means of translating a fixed term investment into a cumulatively depreciated asset. In this section, we test the importance of this assumption by comparing the results from calibrating incremental capital flow payments between the models to the results from calibrating incremental overnight capital costs between the models.

To use the hybrid linking approach in Section 3.2 while calibrating the frameworks using incremental overnight capital costs, we need to generate a set of incremental capital flow payments that will require an increase in the SAGE-PE capital stock consistent with the overnight capital costs in the power sector PE model. To do this we calculate capital flow payments based on changes to overnight capital with internally consistent rates of return and depreciation from the SAGE model, relying on the capital flow equation:

$$k_{t,r} = k_{t-1,r}(1-\delta) + inv_{t-1,r} \tag{18}$$

where $k_{t,r}$ denotes the stock of capital in period t and region r, δ the assumed depreciation rate, and $inv_{t,r}$ represents investments made toward capital. We perturb baseline investments to match the change in overnight capital costs for both new and existing generation to calculate the implied change in the capital stock and associated rental payments (noting that all capital investments made toward existing generation accrue to "new" capital in the SAGE model). Letting $k^*_{t,r}$ and $pr^*_{t,r}$ denote the baseline levels of capital and associated rates of return and $k^{on_v}_{t,r}$ denote the stock of capital with changes induced by incremental overnight capital investments for generator vintage, v, the flow of capital payments are calculated as:

$$fk^{sage}_{t,r,v} = pr^*_{t,r}(k^{on_v}_{t,r} - k^*_{t,r}) \tag{19}$$

This approach can lead to significant differences in capital flow payments. Figure 11 describes the illustrative incremental costs across capital payment assumptions. Relative to the main scenario (labeled, "IPM Capital Accounting"), accounting for capital flow payments using internally consistent SAGE rates produce relatively uneven capital flow payments. SAGE assumes a larger economy-wide baseline interest rate (4.5%) and a differential depreciation schedule than the assumed rates in IPM and therefore capital payments are larger in the first two model periods. As large changes in overnight capital in early model years depreciate in the SAGE model, payments decline. Because capital is an infinitely lived asset in SAGE that cumulatively depreciates, capital flow payments persist after 2056 and are negative due to negative changes in overnight capital (reported in Figure 3).

These differences produce changes in the estimated costs generated through the linked framework. Table 3 reports the annualized cost estimates for the incremental PE costs (e.g., assumed IPM costs), calibrated engineering costs of compliance, and GE social costs. Aggregate social costs fall by 4% under the SAGE capital accounting approach relative to the IPM approach as the reductions in capital payments from 2041 onward outweigh increases in capital payments in 2031 and 2036 in the aggregate annualized metric. Notably, engineering compliance costs and incremental PE compliance costs are

Figure 11: Illustrative Incremental Costs by Capital Payment Assumption

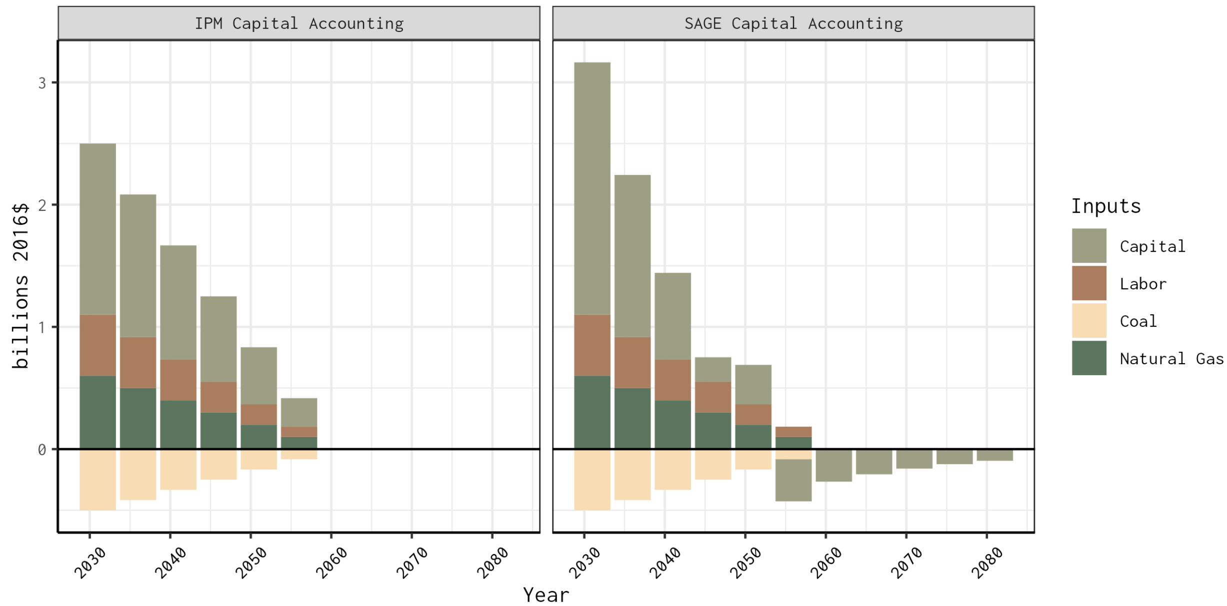


Table 3: Annualized Social, Incremental PE, and Engineering Compliance Cost Estimates by Capital Assumption (billions 2016$)

	IPM Capital Accounting	SAGE Capital Accounting
Incremental PE Costs	0.59	0.58
Engineering Compliance Costs	0.64	0.64
GE Social Costs	0.77	0.73

Notes: Social costs are calculated as equivalent variation. Present values and annualized cost estimates are calculated by interpolating between model years, assuming an infinite horizon, and are based on the internal discount rate in SAGE of 4.5 percent.

relatively unaffected suggesting that the change in the social cost is dependent on the tax interaction effects described above.

Sectoral output and labor demand impacts are as expected; relative to the main simulations, impacts are larger in 2031 and 2036 where aggregate incremental costs are greater in the SAGE capital case and smaller onward due to reductions in incremental compliance costs. Figure 12 reports the distributional social costs across capital accounting assumptions. Because the changes in the incremental costs induced from the alternative assumption on capital accounting are concentrated in capital flow payments, richer households are relatively more impacted than poorer households as they derive more of their income from returns to investments. The SAGE capital accounting produces incremental costs that are relatively less capital intensive and therefore, richer households are less burdened by reduction in capital income from diverting investments to less productive uses relative to the baseline.

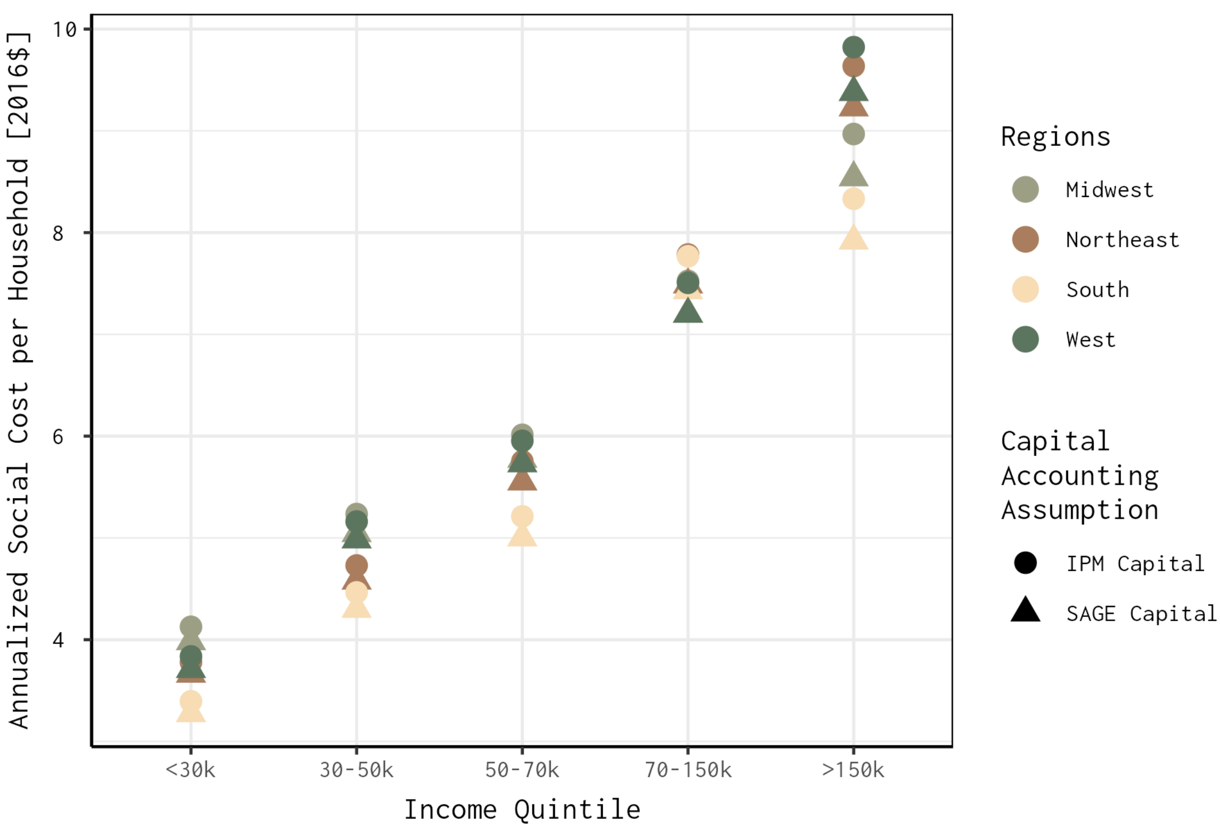
4.4.2 Sensitivity: Alternative Baseline Based on AEO 2023

The linking approach outlined in this paper relies on incremental costs to avoid issues related to harmonizing the SAGE model and its baseline with an approximate structure of a detailed sector model such as IPM. Often, in an iteratively linked framework, baseline adjustments must be made to the models to sensibly exchange variable outcomes (SAB, 2017). In this section, we test the importance of baseline differences between models on the overall economy-wide impacts produced by the hybrid linked framework. We compare model outcomes of the default version of SAGE to outcomes produced by a version of the SAGE model that has been recalibrated to match electricity sector trends from updated Annual Energy Outlook (AEO) projections published by the U.S. Energy Information Administration.

The SAGE model baseline (v.2.1.0) is calibrated to the 2018 AEO and therefore, does not capture environmental regulations in place after 2018 in the electricity sector, nor does it capture changes in the electricity sector induced by the Inflation Reduction Act. To evaluate the effect of these differences, we create a version of the SAGE baseline calibrated to the 2023 AEO, which is inclusive of updated environmental regulations and many of the provisions in the Inflation Reduction Act.[30] To

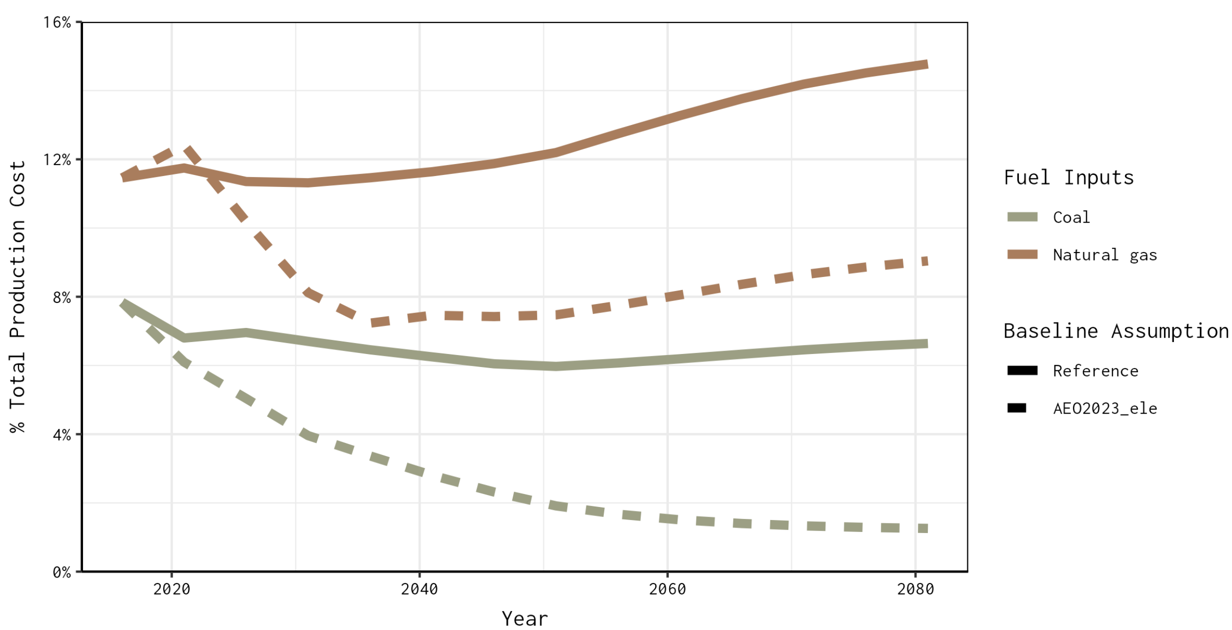
[30]See https://www.eia.gov/outlooks/aeo/IIF_IRA/ for a discussion of changes in projections in energy markets due to IRA provisions.

Figure 12: Distribution of Annualized Social Costs per Household by Capital Assumption (2016$)



limit the scope of this sensitivity, the alternative SAGE baseline, denoted here as `AEO2023_ele`, is only reflective of the updated projections in generation trends in the electricity sector. We calibrate SAGE to projections in the 2023 AEO by targeting growth of demand for coal, natural gas, and refined petroleum in the electricity sector. Reductions in fossil inputs are reallocated to capital and labor to approximate a shift in generation towards renewables reflective of the projections. We do not attempt to explicitly model mechanisms for subsidizing low emitting technologies nor incorporate updated projections throughout the rest of the economy such as projected changes in the electrification of sectoral production and final consumption expected from the Inflation Reduction Act. It is beyond the scope of this sensitivity analysis to assess the broader economy-wide implications of impacts of the IRA outside of the electricity sector. Figure 13 reports the percent of total production costs attributed to coal and natural gas input demands in the electricity sector across baseline assumptions. The SAGE `AEO2023_ele` baseline shows a decline in coal use that approximates reductions in coal generation in the IPM baseline.

Figure 13: % Costs of Coal and Natural Gas Use in the Electricity Sector



Under the main illustrative policy scenario, assumed incremental compliance costs are unchanged across baseline assumptions. However, calibrating SAGE-PE under the alternative baseline produces different calibrated productivity parameters relative to the default baseline. The incremental costs of reductions in coal use and increases in natural gas represents a larger share of the `AEO2023_ele` baseline relative to the default version and therefore calibrated productivity parameters are relatively larger in absolute value for coal and natural gas inputs and smaller for capital and labor inputs (capital and labor demands are relatively larger in the electricity sector relative to the reference baseline due to assumptions on the role of renewables).

Table 4 reports annualized representative engineering compliance, PE and social costs. PE compli-

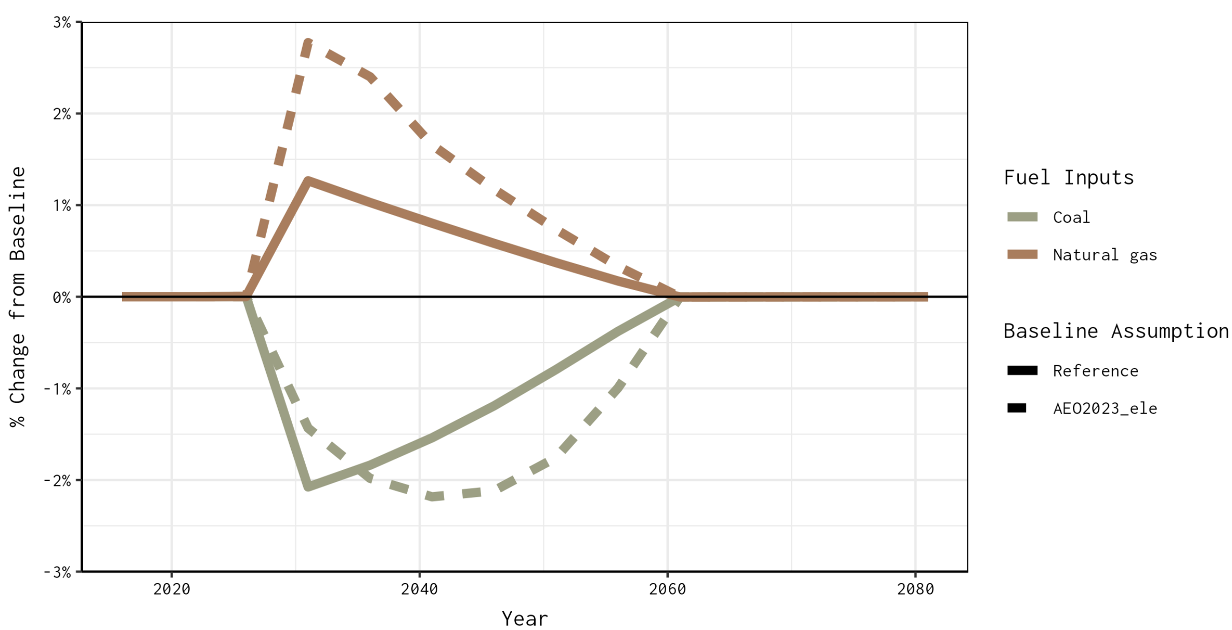
Table 4: Annualized Social, Incremental PE, and Engineering Compliance Cost Estimates by Baseline Assumption (billions 2016$)

	Reference Baseline	AEO2023_ele Baseline
Incremental PE Costs	0.59	0.59
Engineering Compliance Costs	0.63	0.64
GE Social Costs	0.77	0.82

Notes: Social costs are calculated as equivalent variation. Present values and annualized cost estimates are calculated by interpolating between model years, assuming an infinite horizon, and are based on the internal discount rate in SAGE of 4.5 percent.

ance costs are equivalent across SAGE baseline assumptions by construction and calibrated engineering costs of compliance are also similar, suggesting that changes in calibrated productivity parameters are offset by changes in the baseline. The baseline assumption does, however, affect social costs. GE social costs under the AEO2023_ele baseline are roughly 7% larger than under the default SAGE baseline. Given the way that energy intensities are calibrated across baseline assumptions, the size of the illustrative policy relative to the value of output in the electricity sector is roughly similar. Therefore, changes in social costs are induced by differences in the cost structures for electricity production across baselines. Furthermore, the AEO2023_ele baseline is calibrated by increasing factor demands in the electricity sector to offset reductions in fossil inputs leading to differences in equilibrium wages, rental rates, labor supply, and stocks of capital which augment tax interactions effects propagating throughout the economy.

Figure 14: % Change in Coal and Natural Gas Use in the Electricity Sector by Baseline Assumption



In percentage change terms, Figure 14 shows the change in coal and natural gas input use in the electricity sector across baseline assumptions. The functional assumptions in SAGE allow for substitutability across fuel inputs in production. Baseline levels of natural gas and coal use are lower while the size of the compliance requirements remains constant, so percent increases (reductions) in natural gas (coal) are typically larger in the `AEO2023_ele` baseline. In initial policy years, increased demand for natural gas bids up the natural gas price leading to an incentive to substitute towards other fossil inputs including coal demand. However, as the input intensity of coal declines in the alternative baseline but remains constant in the assumed policy scenario, the ability to substitute is mitigated leading to relatively larger percent reductions.[31]

Figure 15: % Change in Real Output Prices in 2031 by Baseline Assumption

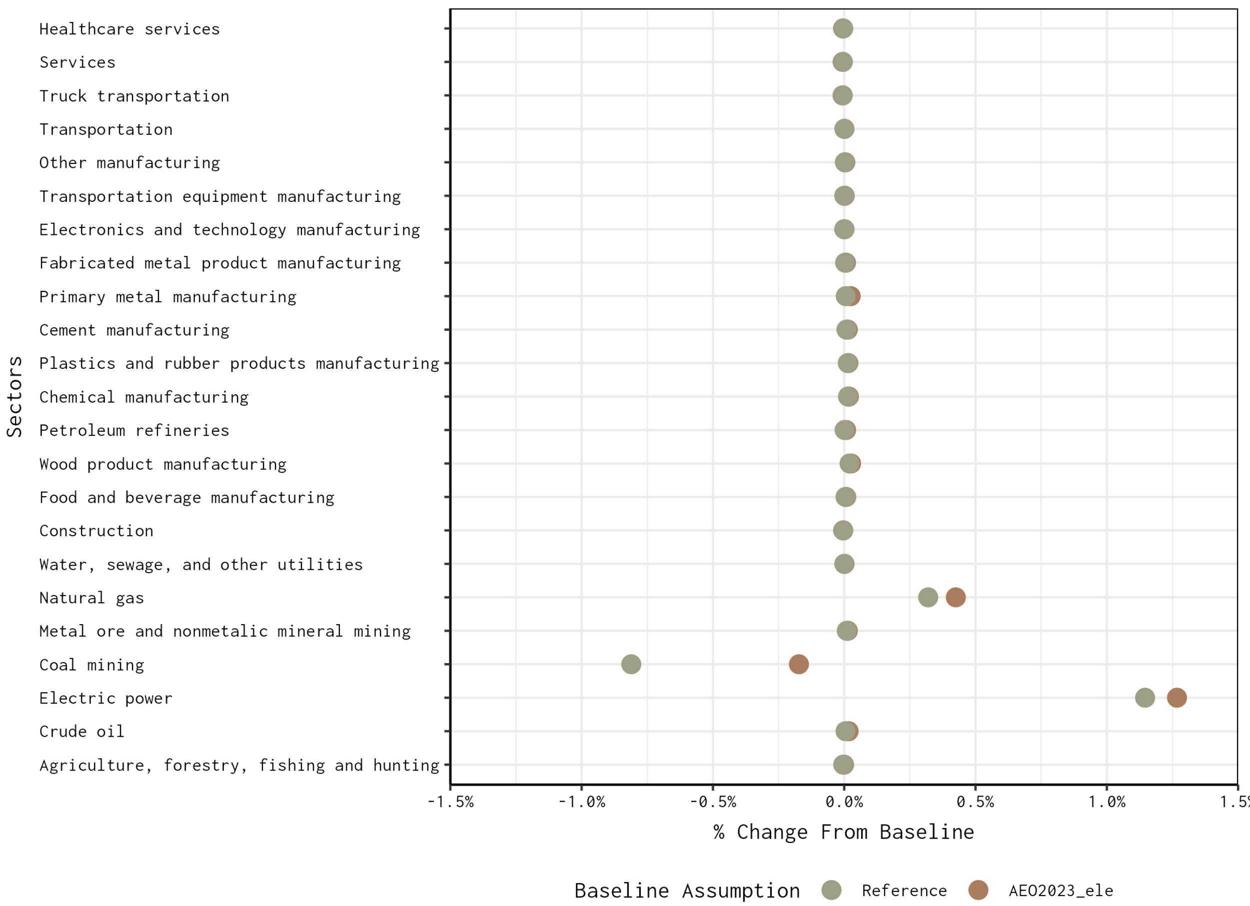


Figure 15 reports the percent change in real output prices in 2031 by baseline assumption. Under the alternative baseline, the increase in the electricity price is expected to be larger than the increase under the default baseline as substitution away from fossil fuel inputs to minimize the costs of compliance becomes more costly given the substantial transition of the sector under the baseline. The

[31] SAGE models production through nested constant elasticity of substitution functions. Inputs that constitute a small share of the total cost of production tend to be on flatter parts of the isoquant and therefore, small price changes can lead to differential percent changes in quantities across inputs.

larger increase in the electricity price increases the economy-wide impacts of the illustrative policy and contributes to the larger social cost estimate. Furthermore, reduced demand for fossil inputs in the `AEO2023_ele` baseline leads to relatively smaller baseline fossil fuel prices compared to the default baseline. Because the size of the shock is unchanged across scenarios, the natural gas price increase is greater in the `AEO2023_ele` baseline due to added natural gas costs being a larger proportion of baseline input demands. This induces greater substitution among fossil inputs, mitigating the price response of coal.

5 Discussion

In this paper, we describe a hybrid linking approach developed to align a CGE model with a detailed sector model when iteratively linking the two frameworks is infeasible. The approach relies on carving out a PE sub-model of the CGE model that aligns endogenous variables, as much as possible, with endogenous aspects of the detailed sector model. Using the sub-model, we construct tools to calibrate the PE response in the regulated sector to incremental costs produced by the detailed sector model. We then illustrate how endogenizing the rest of the CGE model produces a different GE solution that is consistent with PE compliance behavior. In our illustrative exercise of modeling a regulation in the electricity sector, we find that the linking approach produces credible economy-wide results and that the GE social cost estimate from the SAGE model is roughly 29% higher than stylized incremental PE compliance costs representative of power sector modeling outputs. However, we note that we only consider a single stylized example in this paper. The magnitude of the difference between the GE social costs and incremental PE costs in the linked framework is likely highly dependent on the input composition of the illustrative shock.

This paper abstracts away from many of the logistical data challenges one would face when adapting sector model outputs for use as CGE modeling inputs. In a real-world setting, aligning the outputs of the detailed sector model for use in the linking framework may require some translation. Often-times, sector model outputs are resolved at different levels of aggregation relative to a more aggregate CGE model. For instance, analysts may need to map time steps and regions between models. Typically, sector model time steps can be mapped to the nearest time step of the CGE model but may require some level of aggregation if the sector model is resolved at sub-annual time steps. Aligning model time steps can be further complicated by the choice of how one chooses to translate capital payments between models. For instance, if an analyst deems it appropriate to align models using changes in overnight capital costs and model time steps do not align between the sector model and the CGE model, the methodology presented in this paper may need to be altered to align the timing of investment behavior and amortized capital payments. A sector model may also have greater regional disaggregation than the CGE model and these regions may not be defined based on Census boundaries requiring a mapping rule (e.g., based on region centroids, areal apportionment based on generation, etc.). While sector modeling outputs will often need to be aggregated to the level of resolution in the CGE model, it may also be that some sector model outputs need further disaggregation (e.g., separating delivered fuel costs and attributing variable and fixed operations and maintenance costs to specific input categories).

There may also be instances when sector model features and outputs do not align precisely with the structure and input requirements of the CGE model. For example, in this illustrative exercise we have attributed incremental costs on existing and new generation to production with extant and new capital, respectively. If the CGE model distinguishes capital vintages like SAGE, production with extant and new capital is not necessarily equivalent to existing and new generation in a power sector modeling framework. It is possible that the linked framework may over-attribute incremental costs to less flexible production processes under this assumption. Detailed partial equilibrium sector models may also include costs to the sector that are appropriate for characterizing private compliance behavior but inappropriate to characterize the social costs of a regulation. Private costs to the sector may be inclusive of taxes, subsidies, and other transfers. To capture the real resource use in the economy in the form of a social cost, the CGE model would require inputs that are net of these payments. For instance, if a capital input is taxed in the sector model and incremental capital costs are inclusive of the tax, the linking framework would cause the CGE model to build more capital than what is actually required to characterize resource uses in the economy. Instead the tax payments need to be removed from the incremental capital costs prior to the calibration exercise to capture the expected incremental resource requirements need for compliance.

The hybrid approach outlined in this paper is subject to several advantages and some limitations. We have found that the hybrid linking framework described in this paper provides a reasonable means to translate impacts from a detailed sector model into GE impacts when iteratively linking models is not possible. The approach allows the model linkage to be easily implementable in the rule development schedule, does not require additional model runs other than what is already completed for a typical rule, and is open-source and reproducible. While our illustrative exercise focuses on the electricity sector, the approach could be applied to other sectors in the economy where a detailed sector model is used to capture regulated sector compliance behavior.

However, the approach is also subject to some caveats. First, the stylized example in the electricity sector produced limited price impacts in upstream energy markets. Future work may explore how alternative characterizations of natural resource supply and demand in the SAGE model may affect responsiveness in SAGE-PE and impact the hybrid linkage approach. In a sensitivity analysis, we also found that baseline differences may be important in characterizing social costs and distributional impacts of a policy. Data underlying the default version of SAGE ranges from 2016 to 2020, depending on the specific source and as a result, recent changes in the economy, including new regulations, may not be captured in the source data used to calibrate the model's baseline. Therefore, interactions between the hypothetical regulation described in this paper and other potential activities induced by other policies may not be explicitly captured in SAGE.

The hybrid linking methodology used to align a detailed sector model and a CGE model accounts for PE feedbacks in determining the GE solution and therefore represents an improvement over assuming the solution of one model directly in the other without iterating. While a full model linkage, where the models iteratively pass information back and forth until jointly converging to an equilibrium, may provide a more complete representation of the economy-wide impacts of regulations, it is challenging to implement given the realities of conducting analyses within a regulatory time frame. The hybrid approach achieves similar aims as the iterative link. However, the efficacy of the hybrid approach is not something we can currently test relative to the iterative approach. We save this explicit comparison for future research.

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A Constructing Illustrative Capital Payments

The illustrative policy assumes a certain portion of the costs are attributed to capital payments associated with changes in capital investments (positive or negative) induced by a rule (e.g., retrofits of control technologies, accelerated new builds, or retirements). The characteristics of capital investments depend on whether they are targeted for existing or new generation. Investments made for existing generators typically represent retrofit pollution control technologies with a shorter economic lifespan whereas investments made for new builds are more representative of new plants with a longer economic lifespan. For this reason, we formulate a mathematical program to solve for the portion of the aggregate capital flow payments assumed in Figure 2 assigned to new and existing generation and consistent changes in overnight capital payments simultaneously (see Figure 3).

Consistent with the assumptions made in this paper, suppose we know the aggregate incremental costs attributed to the flow of capital payments across time and region, $shock^k_{tr}$. We aim to solve for the portion of that capital payment attributed to existing and new generators. Let crf_v denote the capital recovery factor by generator vintage, v (as defined in Equation 17), ok_{trv} represent the overnight capital costs in time period t, region r, and vintage v, fk^{pe}_{trv} the amortized capital flow payments, and θ_{trv} the endogenous share of the capital payments attributed to existing or new generators. We formulate a constrained least squares optimization problem that minimizes the difference of the endogenous share associated with capital payments to existing and new generators from the baseline share of production with extant and new capital in the SAGE model ($\overline{\beta_{trv}}$).

$$
\begin{aligned}
\min_{\theta_{t,v,v}} \quad & \sum_{t,r,v} shock^k_{t,r} \left(\frac{\theta_{t,r,v}}{\overline{\beta_{t,r,v}}} - 1 \right)^2 \\
\text{subject to} \quad & fk^{pe}_{t,r,v} = shock^k_{t,r} \theta_{t,r,v} \\
& fk^{pe}_{t,r,'existing'} = \sum_{tt \in E(tt,t)} crf_{'existing'} ok_{tt,r,'existing'} \\
& fk^{pe}_{t,r,'new'} = \sum_{tt \in N(tt,t)} crf_{'new'} ok_{tt,r,'new'} \\
& \sum_{v} \theta_{t,r,v} = 1
\end{aligned}
$$

where $E(tt, t)$ and $N(tt, t)$ denote the subset of model years starting in time tt that capital payments need to be made from a change in the overnight capital for existing (15 years from time period tt) and new (30 years from time period tt) generation. Minimizing based on the share of production with extant and new capital biases capital payments toward existing generation in early years and new generation in later model years. See Figure 16 the calculated shares of capital by new and existing generation.

Figure 16: Calibration Verification