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Abstract: New York is considering additional emission regulation on top of its obligations under the Regional Greenhouse Gas Initiative (RGGI) to achieve its State Energy Plan targets. The proposed measure is a so-called "carbon adder" on CO_2 emissions from the power sector which is set as the difference between the targeted social cost of carbon and the prevailing RGGI price for CO_2 emission allowances. We investigate the potential economic and environmental impacts from the imposition of a carbon adder on New York's power sector. While our analysis indicates the risk of excess cost through overlapping regulations, we find that the carbon adder gives the "right" price signal for New York's power generation to turn into a greener one. Market requirements for permit price floors in the RGGI market induces carbon permit retirements across RGGI states leading to small reductions in region- and country-wide emissions levels.

JEL classifications: D61, H21, H22, Q58

Keywords: Environmental regulation, overlapping regulation, emission taxes, emissions trading

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1. Introduction

In the United States, limited federal requirements on greenhouse gas (GHG) emissions has prompted some state level reactions to reduce their respective carbon footprint. In New York, the State Energy Plan was designed in 2015 to reduce the state's GHG emissions by 40% in 2030 and by 80% in 2050, relative to 1990 levels. To achieve these reductions, the plan requires that 50% of electricity be generated from renewable energy sources by 2030. As of 2016, the electricity sector accounted for more than 16% of New York State's GHG emissions.[1] New York also participates in the Regional Greenhouse Gas Initiative (RGGI), a central cooperative policy in nine US Northeast and Mid-Atlantic states for curbing GHG emissions in the electricity sector.[2] The stringency of the cooperative agreement has lead state regulators to question whether participation in RGGI will achieve the State Energy Plan targets alone. In this paper, we assess the economic implications of New York unilaterally targeting a desired state level cost of carbon amid overlapping regulations spanning other regions in the United States. We find that due to the cap on emissions imposed by RGGI, transitions towards a greater share of renewable energy in New York is complemented with increases in fossil fuel-based production in other states covered by the market's cap on emissions. However, institutional features of the market prevent a complete reallocation of emissions to other RGGI states, leading to small reductions in overall country-wide emissions levels.

RGGI is a market-based emissions cap-and-trade system designed to reduce emissions of CO_2 (as the major GHG) by the power sector in a cost-effective manner across RGGI states. Compliance obligations apply to fossil-fuel power plants with generation capacities of 25 MW and beyond. Under RGGI, the power plants are required to hold CO_2 allowances equal to their CO_2 emissions (over three-year control periods). Each RGGI state issues a limited number of CO_2 emission allowances that can be traded across all RGGI states.[3] The primary objective of emissions trading is to achieve cost savings relative to purely state-level action. Trading assures that emissions are abated where it is cheapest by equalizing marginal abatement costs across all emission sources covered by the cap.

Due to generous allocations of emission allowances, however, RGGI carbon prices were low over the last decade. Figure 1 shows the evolution of the RGGI allowance clearing price since the program went into effect in 2009. The total cap has been adjusted twice since 2009 as illustrated in Figure 2.

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[1] See: https://www.eia.gov/environment/emissions/state/.

[2] The program covers electricity production in Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

[3] In addition, there are Clean Energy Standards (CES) that provide the procurement of Renewable Energy Credits (RECs) to attract investment in new renewable electricity generation and the procurement of Zero Emission Credits (ZECs) to retain existing nuclear generation.

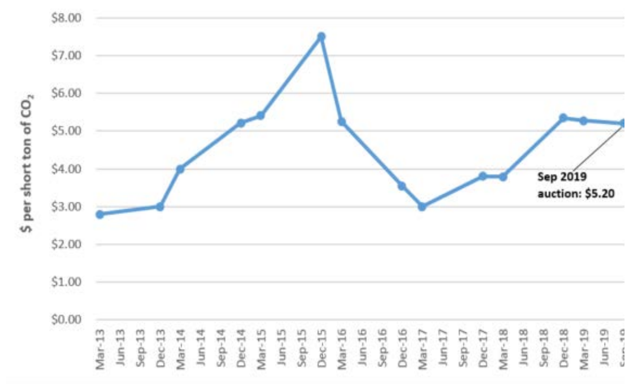

Figure 1: RGGI allowance clearing price (source: www.rggi.org)

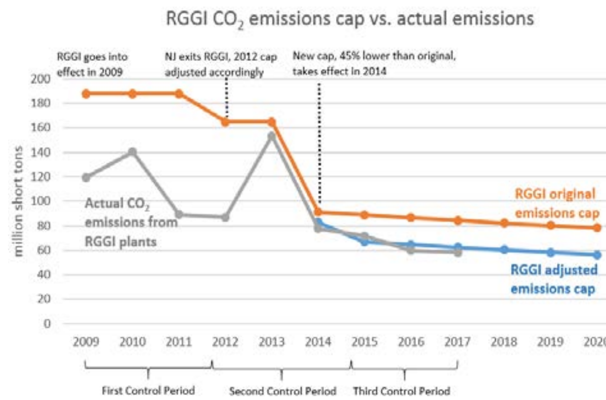

Figure 2: RGGI CO_2 emissions cap versus actual emissions (source: www.rggi.org)

The first adjustment took place after New Jersey exited the RGGI program in 2012 and the second adjustment took effect in 2014 by fixing the total cap at 55% of the original level in 2009. While these adjustments enhanced the scarcity of emission allowances, the CO_2 emission prices remained low limiting incentives for long-term investments into CO_2 abatement. The highest price level realized in the November 2015 auction amounted to \$7.5 per short ton of CO_2, while latest auction price in September 2019 was just \$5.20 per short ton of CO_2.[4] Climate protection activists perceive the low RGGI prices as a serious threat of locking emissions in the long run and hindering a faster transition towards carbon-free (renewable) energy sources. They point to the drastic difference between RGGI prices and the range of estimates for the social cost of carbon which is a commonly employed metric of the expected economic damages from CO_2 emissions (Griffiths et al., 2012). While estimates for the social cost of carbon vary, the New York Public Service Commission (NYPSC) has called for adopting the estimate by the US Interagency Working Group of \$42 per metric ton of CO_2 as of today rising to \$50 per metric ton of CO_2 by 2029[5] which is an order of magnitude higher than the actual RGGI prices (Interagency Working Group on Social Cost of Carbon, 2016).[6]

[4] The short ton is a unit of weight (most commonly used in the US) equal to 2,000 pounds (907.18474 kg). If not explicitly labelled as short ton, we refer to a ton as a metric ton. Note that 1 short ton is approximately equal to 0.9 metric tons.

[5] The UK Government's 2007 Stern Review put marginal social damages from climate change at $US 85 per ton of CO_2. In 2010, the US Government, estimated marginal social damages for the first time and set the value at $US 21 per ton of CO_2.

[6] Estimates of the social cost of carbon are denoted in 2007 US dollars per metric ton of CO_2. Over the past decade, the US Interagency Working Group has estimated the social cost of carbon that monetizes climate damages from

To achieve this target, New York is considering a carbon adder for its electricity market which closes the gap between the RGGI price and the socially desirable CO_2 price. The principal reasoning behind the adder is not new. Palmer, Burtraw and Keyes (2017) refer to "environmental" adders in the 1990s which were used by utility regulators in various US states to identify least-cost resource investment options taking into account both private and external costs to the power generators. However, environmental adders were just used as "shadow prices" on criteria pollutants without being actually charged to companies or their customers. The recent carbon adder proposal by NYPSC on the other hand is designed to operate as a sector-specific carbon tax equal to the marginal environmental damages from carbon emissions that is not already covered under existing carbon policies (NYPSC, 2016). As an explicit price signal, the carbon adder is expected to provide stronger incentives for local levels of decarbonization within the electricity sector, such as investments in gas-fired combined cycle generation or renewable power plants.

From an economic efficiency perspective, the use of multiple policy instruments – here: RGGI and a carbon adder – to pursue a single policy objective – here: CO_2 emissions reduction – will be counterproductive or at best redundant (Johnstone, 2003). Böhringer et al. (2008) note that the price-based mechanism of an emission tax to complement the quantity-based mechanism of a cap-and-trade system will not change the environmental effectiveness of the latter unless the cap becomes non-binding (i.e. there is a full crowding out of the quantity mechanism). Furthermore, such overlapping regulation will trigger cost inefficiencies to the extent that additional emission taxes are only imposed partially on emission sources covered by the cap-and-trade system since marginal abatement cost are no longer equalized across all emission sources.[7]

This paper quantifies the economic and environmental impacts of imposing a carbon adder on electricity generation in New York in the context of the existing RGGI regulation. We first present comparative static results from a stylized analytical model to highlight fundamental response

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carbon emissions, accounting for damages to human and ecosystem health, agricultural productivity and property damages due to increased flood risk. Its 2016 report provides annual values for the social cost of carbon over the period from 2010 to 2050 using alternative discount rates of 2.5, 3 and 5 percent. The NYPSC adopted the social cost of carbon as estimated with a 3 percent discount rate, starting at \$42 per metric ton of CO_2 in 2020, and increasing up to \$69 per metric ton of CO_2 by 2050.

[7] A mix of differentiated policy instruments may be justified if there are multiple policy objectives, such as social or technology-related criteria that may conflict with narrowly defined efficiency considerations (Tinbergen, 1952). The reasoning behind could stem from the pre-existence of multiple market imperfections such as asymmetric information, market power, initial tax distortions, external knowledge spillovers, transaction costs, etc. For example, sector-specific differences in transaction costs have served as an argument for limiting the EU ETS to large-scale stationary industrial combustion plants while applying efficiency standards for CO_2 reduction to the building and traffic sectors.

mechanisms. The stylized partial equilibrium analysis shows that an additional price on carbon in a region already covered by an existing cap-and-trade market causes a downward pressure on the market-wide permit price. This leads to a relocation of emissions from the taxed regions to other regions covered by the emission cap – the so-called "waterbed" effect. For our quantitative impact assessment of the New York carbon adder, we use a large-scale multi-state multi-sector computable general equilibrium (CGE) model of the US economy calibrated to empirical data from the Wisconsin National Data Consortium (Rutherford and Schreiber, 2018). Given the paramount importance of the electricity sector, we pay special attention to the representation of power production through a bottom-up activity analysis characterization where discrete generation technologies compete to supply electricity. Our analysis shows that New York's proposed carbon adder may have important consequences that are unintended by its protagonists. Firstly, from an emissions perspective, a carbon adder is environmentally ineffective if the emissions cap remains binding across all RGGI regions, merely shifting emissions across RGGI states. However, we find that not to be the case because the carbon adder drives the RGGI price to its price floor, leading to reductions in the carbon cap to maintain a given price level. Secondly, from an economic perspective, the NY carbon adder (as not levied uniformly across all RGGI states) induces excess cost of emission reduction in the power system by driving an explicit wedge between the RGGI carbon price and the effective carbon price faced by the NY electricity market violating the fundamental cost-effectiveness principle of equalized marginal abatement costs. The unilateral carbon adder in NY depresses the RGGI price thereby subsidizing net buyers of allowances and promoting power production by the dirtiest (most CO_2-intensive) power technologies as compared to the cap-and-trade system stand-alone (Böhringer and Rosendahl, 2010).

The remainder of this paper is organized as follows. In section 2, we present theoretical comparative statics from a multi-region partial equilibrium framework. We then present a non-technical summary of the CGE model and its parameterization with empirical data in section 3. Policy simulation results are described in section 4, followed by our conclusions in section 5.

2. Partial equilibrium analysis

We start with an analytical framework akin to Böhringer and Rosendahl (2010), Fischer and Preonas (2010), and Böhringer and Behrens (2015). In each of these papers, the authors develop a partial equilibrium model of the electricity market to understand the implications of overlapping regulations in climate policy where renewable promotion policies such as feed-in tariffs, feed-in premia, or green quotas are imposed on top of a pre-existing emission cap-and-trade system.

The interaction between RGGI states and New York in the supply and demand of electricity is modeled by considering two regions (indexed by *r*) who employ both black (B) carbon emitting generating technologies and green (G) renewable technologies (indexed by *i*) in a competitive power market. Producers of electricity have cost functions $c_r^i(q_r^i)$ where q_r^i denotes the supply of electricity by producer type i in region r. Cost functions are assumed to be twice differentiable where ${c_r^i}' > 0$ and ${c_r^i}'' > 0$. Carbon emitting black technologies have an emissions rate a, such that total emissions can be represented as $e = a(\sum_r q_r^B)$. The market price of electricity across regions is denoted as p^E.[8] The demand for electricity in each region is represented as a downward sloping demand function $D_r(p^E)$ (where $D_r' < 0$).

Producers of electricity are assumed to be price-taking profit maximizers. In the reference situation, we assume that there exists an emissions quota, capping total emissions from the power sector at some exogenous target level $\overline{e}$. The black producers across both regions must buy emissions allowances at a market-wide price, τ, for every generated emission unit. Note that the emissions price is determined endogenously in line with the chosen cap on emissions levels. The profits of the black and green producers are given by:

$$\pi_r^B = p^E q_r^B - c_r^B(q_r^B) - \tau a q_r^B \tag{1}$$

$$\pi_r^G = p^E q_r^G - c_r^G(q_r^G) \tag{2}$$

Maximizing these functions with respect to output yields the following first-order conditions equating the marginal cost of production for both producers with the emissions price:

$${c_r^B}'(q_r^B) + \tau a = p^E \tag{3}$$

$${c_r^G}'(q_r^G) = p^E \tag{4}$$

The electricity market clears across both regions, as does the emissions market:

$$\sum\nolimits_r D_r(p^E) = \sum\nolimits_r (q_r^B + q_r^G) \tag{5}$$

$$\overline{e} = a\left(\sum\nolimits_r q_r^B\right) \tag{6}$$

Equations (3)-(6) represent the system of equilibrium conditions in our partial equilibrium model.

[8] Without loss of generality, we can assume that there is no markup between wholesale supply and retail demand prices.

We then totally differentiate the system to generate responses to additional policy interventions:

$$dq_r^B = (dp^E - a d\tau)/c_r^{B''} \tag{7}$$

$$dq_r^G = dp^E \,/\, c_r^{G''} \tag{8}$$

$$dp^E = \sum_r (dq_r^B + dq_r^G) \,/ \sum_r D_r{}' \tag{9}$$

$$a\left(\sum_r dq_r^B\right) = 0 \tag{10}$$

We solve these equations for dp^E by substituting equations (7) and (8) into equation (9) and simplify to obtain the following expression,

$$dp^E = a(\beta_1 d\tau_1 + \beta_2 d\tau_2) \tag{11}$$

where:

$$\beta_1 = \frac{c_1^{G''} c_2^{G''} c_2^{B''}}{\Gamma}, \quad \beta_2 = \frac{c_1^{G''} c_2^{G''} c_1^{B''}}{\Gamma}$$

and:

$$\Gamma = c_1^{G''} c_2^{G''} c_1^{B''} + c_1^{G''} c_2^{G''} c_2^{B''} + c_1^{G''} c_1^{B''} c_2^{B''} + c_2^{G''} c_1^{B''} c_2^{B''} - c_1^{G''} c_2^{G''} c_1^{B''} c_2^{B''} (D_1' + D_2')$$

It is straightforward to see that $0 < \beta_1 < 1$, $0 < \beta_2 < 1$, and $0 < \beta_1 + \beta_2 < 1$. Increases in the emission price of carbon faced by black electricity producers raises the price of electricity. Note that we make the distinction between $d\tau_1$ and $d\tau_2$ to characterize the interaction of a binding cap on emissions with a region-specific additional price for carbon (which leads to regionally different emission prices τ_1 and τ_2). In the reference situation, $d\tau = d\tau_1 = d\tau_2$. Suppose that region 1 imposes a carbon adder on black electricity technologies. Then the change in carbon pricing for region 1 is $d\tau_1 = d\sigma + d\gamma$, and for region 2, it is $d\tau_2 = d\sigma$ where σ represents the market-wide permit price and γ denotes the "carbon adder". Substituting equations (6), (7) and (11) into equation (10), we obtain:

$$d\sigma = -d\gamma \left(\frac{\beta_1 \left(c_1^{B''} + c_2^{B''}\right) - c_2^{B''}}{(\beta_1 + \beta_2)\left(c_1^{B''} + c_2^{B''}\right) - c_1^{B''} - c_2^{B''}} \right) \tag{12}$$

The denominator of this expression is strictly negative. Therefore, an increase in this additional tax on carbon creates downward pressure on the price of permits whenever $\beta_1 c_1^{B''} < (1 - \beta_1) c_2^{B''}$, which holds unambiguously given our assumptions.

The impact an additional tax has on electricity quantities can be calculated through substituting equation (11) into equations (7) and (8):

$$dq_r^G = \frac{a(\beta_1(d\sigma + d\gamma) + \beta_2 d\sigma)}{c_r^{G''}} \tag{13}$$

$$dq_1^B = \frac{a\big((\beta_1 - 1)d\gamma + (\beta_1 + \beta_2 - 1)d\sigma\big)}{c_1^{B''}} \tag{14}$$

$$dq_2^B = \frac{a(\beta_1 d\gamma + (\beta_1 + \beta_2 - 1)d\sigma)}{c_2^{B''}} \tag{15}$$

The production of electricity from both green technologies and black technology in the region without an additional tax increases with an increase in $d\gamma$. Equivalently, production in region 2 decreases with increasing permit prices. An increase in $d\gamma$ in region 1 leads to decreases in electricity production from the black technology whereas output by black producers in region 2 increases. Total emissions across both regions remain at the exogenous level $\overline{e}$ as long as the additional tax does not fully crowd out the market-wide emissions price and thereby renders equation (6) non-binding.

3. Numerical CGE model for applied policy analysis

Our theoretical partial equilibrium analysis provides insights into key mechanisms triggered by the introduction of a region-specific carbon tax on top of a pre-existing multi-region cap-and-trade system. However, the theoretical analysis focuses on a stylized electricity market and abstracts from more complex substitution, output, and income effects across the economy. We therefore develop a multi-state multi-sector computable general equilibrium (CGE) model of the US economy to quantify the economic and environmental impacts of alternative carbon pricing regulations in New York based on empirical data.

Below, we first provide a non-technical model description followed by a short description of the database underlying the model parametrization. A detailed algebraic model description is provided in Appendix A.

3.1 Non-technical model summary

Our CGE model builds on the core logic of canonical multi-region multi-sector computable general equilibrium models (e.g. Lanz and Rutherford, 2016). Decisions about the allocation of resources are decentralized, and the representation of behavior by consumers and firms follows the standard microeconomic optimization framework: (i) consumers maximize welfare through private consumption subject to a budget constraint; (ii) firms combine intermediate inputs and primary factors at least cost for given technologies. By default, labor and capital are treated as mobile across sectors within a region while specific resources are tied to sectors in each region. Preferences and technologies are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to changes in relative prices.

Production in industries other than fossil-fuel extractive sectors and power generation is described by 3-level nested constant-elasticity-of-substitution (CES) functions which characterize the price-dependent trade-offs between material inputs, energy, and value-added components. The top level of the function describes the trade-off between material inputs and an aggregate of value-added and energy inputs. The second level is characterized by trading off an energy composite with a value-added (factor) composite. At the third level, the energy aggregate is composed of electricity and other fossil fuels (along with associated emissions) while the value-added aggregate is composed of labor and capital. The production structure of extractive fossil fuel sectors (crude oil extraction, coal mining, natural gas extraction) and electricity (for specific power generation technologies) is captured by a single-level CES function. For extractive fossil fuel sectors, we use resource shares of capital from EPAs SAGE model (Marten and Garbaccio, 2018) to approximate portions of capital that represent the finite resource.[9] We assume that the entire capital stock represents the fixed factor for power generation technologies. Resources or capital in these sectors (and technologies) is treated as sector-specific and trades off with a Leontief composite of all other inputs at a constant elasticity of substitution. The substitution elasticity between the specific factor and the Leontief composite at the top is calibrated to exogenously chosen supply elasticities (values used for extractive sectors are taken from Marten and Garbaccio (2018)). Supply elasticities for renewable sources are taken from the EPPA model (Chen et al. 2015). The electricity production sector is decomposed into discrete generation technologies based on primary fuel use. We operationalize the electricity sector decomposition by assuming that electricity production receives the same output price regardless of the generation technology used.

The demand side of the model is captured by representative regional households and governments in each US state. Both, households and governments demand their final consumption composite and public goods bundle, respectively, according to price-responsive CES preferences. Households are endowed with factor income from labor, capital, and sector-specific resources while regional governments receive income from taxes minus subsidies. Lump-sum transfers between the regional government and the regional representative household assure income-expenditure balances taking into account a fixed balance of payment surplus or deficit for each state and fixed investment demands by region. In

[9] Using data from the Energy Information Administration (EIA) and performing a literature review for extractive sectors, Marten and Garbaccio (2018) find that the return to the natural resource, relative to man-made capital is 25% for oil and natural gas extraction and 40% for coal mining.

counterfactual-policy simulations the lump-sum transfers between governments and households are adjusted endogenously to warrant an equal-yield constraint, i.e. the constant provision of public goods at base-year levels.

Structural unemployment in the United States is captured through an empirical relationship known as a wage curve (e.g. Blanchflower and Oswald, 1994). The wage curve is a reduced-form function which relates increases in the real wage rate to decreases in structural unemployment.[10]

Trade between US states and the rest of the world is specified following the Armington approach of product heterogeneity, where domestic and foreign goods are distinguished by origin (Armington, 1969).[11] Produced goods are allocated to either the regional, national, or foreign markets. For non-electricity goods, the national market is assumed to be pooled (as we lack explicit bilateral trade flows across US states). An elasticity of transformation is assumed to govern the disposition of goods into the various regional markets. Domestic absorption is composed of state-level demand, national demand, foreign demand and trade margins. Aggregate electricity demand also includes explicit bilateral demands. Armington elasticities of substitution govern the trade-offs in state-level (regional) demands between regionally, nationally, and internationally produced goods.[12]

3.2 Data

The data used for the analysis is based on state-level input-output accounts produced by the Wisconsin National Data Consortium (WiNDC) for the year 2016. WiNDC provides an open source build routine for generating micro-consistent state-level datasets based on national US data from the Bureau of Economic Analysis (BEA).[13] National supply and use tables are reconciled in the routine by using a matrix balancing routine to enforce standard input-output accounting identities. The core dataset relies on regional level datasets to share out the national data towards the desired level of regional specification. Shares are derived from (regional) state level data on gross product, personal consumer expenditures, state government finances, national commodity flows, and foreign trade.

For energy and emissions accounting, an energy-environment sub-routine of WiNDC is used that ensures that the state-level input-output accounts incorporate information on physical energy demands, supplies and prices based on the State Energy Data System (SEDS). The sub-routine distinguishes between

[10] In our model parametrization, we adopt an empirical estimate of -0.1 for the elasticity of the real wage with respect to the unemployment rate.
[11] In international trade, the US is assumed to be a price-taker.
[12] Based on empirical evidence from complementary data sources such as GTAP (Narayanan, Aguiar, and McDougall, 2015) we assume that nationally and regionally produced goods are more substitutable relative to foreign imports.
[13] This process is described in detail in Rutherford and Schreiber (2018).

the supply price of energy (defined as the minimum of all demand prices across the country for a given energy source) and demand prices. As a result, trade margins are adjusted to capture differences between wholesale and retail prices. To account for bilateral trade flows in the analysis, SEDS state level net generation data is used to approximate electricity trade flows based on a linear program which satisfies net generation while picking the closest destination for national supply/demand. Net generation provides an aggregate measure of the relative magnitudes of national level electricity imports and exports for a given state. The routine also restricts trade to be within and between adjacent electricity markets.[14] The sub-routine also separates the crude oil and natural gas extraction sector based on production data.

For our analysis of the carbon adder, we extend the dataset to further disaggregate the electricity generation sector into discrete generating technologies. We separate the value of aggregate electricity production based on regional-level shares of electricity generation by technology type in SEDS and verify that fuel-specific generating technologies (coal, natural gas, and oil) are allocated the corresponding intermediate inputs as provided by the input-output accounts. We furthermore use emissions factors from the Energy Information Administration to translate physical energy demand quantities by discrete technologies into carbon emissions.

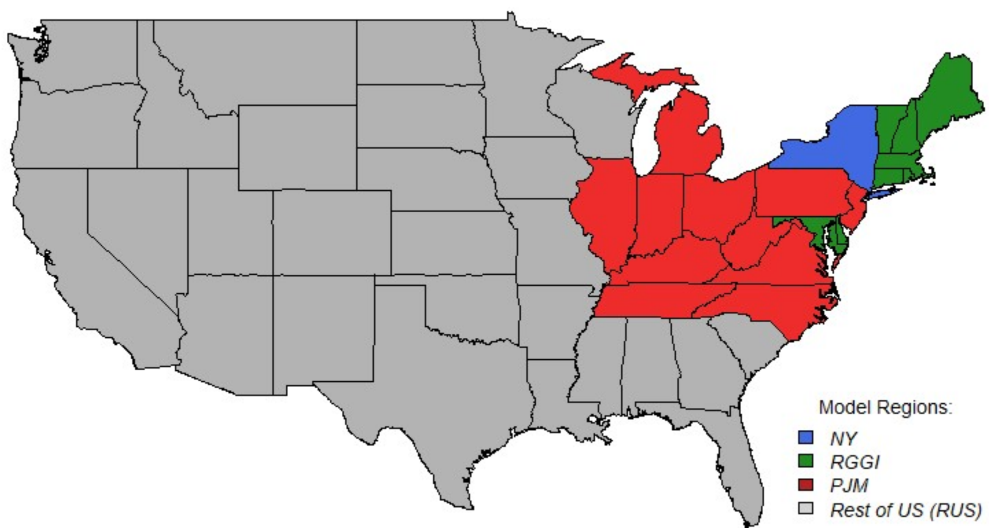

Figure 3: Model regions[15]

[14] States are aggregated to model regions and assigned to electricity markets (CAISO, MISO, ISONE, NYISO, NW, PJM, SE, SW, SPP, TEXAS). Note that if multiple electricity markets span a given model region, more than one market is used to constrain the optimization routine. The routine also imposes a lower bound on regional electricity trades based on the level of aggregate supply in origin regions and demand in the destination region.

[15] While not pictured, Alaska and Hawaii are part of the "Rest of US" modeling region.

Table 1 lists the regions (see also Figure 3), sectors, and electricity generating technologies in the data aggregation used for our numerical CGE simulations. Apart from New York (NY), we include an aggregate of other RGGI states[16] whose electricity sectors are regulated by a common emissions cap-and-trade system and thus will be most directly affected by New York's unilateral CO_2 pricing initiatives of electricity-related emissions. Furthermore, the dataset aggregates PJM states (excluding the RGGI states Delaware and Maryland)[17] which jointly operate a competitive wholesale electricity market closely interacting with RGGI states. The rest of US states are merged together in a single aggregate region (RUS). At the sectoral level, our dataset includes all major primary energy carriers (crude oil extraction, natural gas extraction, coal mining) and secondary energy carriers (petroleum refineries, electricity). The dataset also distinguishes composites of energy-/emission-intensive production[18] and transport activities as well as composites for other manufacturing and services. All remaining industries are represented through an aggregate sector (rest of economy).[19] In the bottom-up representation of power generation, we distinguish eight discrete generation technologies covering fossil-fuel based power plants (coal, gas, oil), nuclear power as well as electricity from renewable energy sources (hydro, geothermal, solar, wind).

Table 1: States, sectors, power technologies in the dataset

Regions	Sectors	Power technologies
New York (NY)	Crude oil extraction	Coal
RGGI states - excl. New York (RGGI)	Natural gas extraction	Oil
PJM states (PJM)	Coal mining	Gas
Rest of the US (RUS)	Petroleum refineries	Nuclear
	Electricity	Hydro
	Energy-/Emission-intensive sectors	Geothermal
	Other manufacturing	Solar
	Transportation	Wind
	Other services	
	Rest of the economy	

Table 2 provides aggregate statistics on the composite regional economies in this analysis. Total gross domestic product is given in the first column. New York stands out for the highest GDP among RGGI states.

[16] Connecticut, Delaware, Massachusetts, Maryland, Maine, New Hampshire, Rhode Island, Vermont.

[17] District of Columbia, Illinois, Indiana, Kentucky, Michigan, North Carolina, New Jersey, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia.

[18] We define energy/emission intensive sectors as those with high levels of embodied carbon (>0.5 kilograms per dollar) as reported in Rutherford and Schreiber (2018).

[19] These remaining sectors include wholesale and retail trade and public administration.

The share of value added attributed to electricity production indicates the relative importance of this sector in the overall region's economy. In New York and RGGI states, this share amounts to half a percent which is roughly half of the average in the rest of the country.[20] To capture a region's reliance on electricity trade, we compute the ratio of electricity purchased from outside the state to electricity purchased from the regional or state (in the case of New York) market. New York ranks lowest in its reliance on outside electricity production (aside from the Rest of the US). Note that in our estimation of bilateral electricity trade, the level of national exports and imports is adjusted to account for aggregation bias. We allow for a portion of the state level national export and imports to be demanded within the aggregate modeling regions. This is apparent in the value for the RUS modeling region which is adjusted downward. Column "Total CO_2" provides total CO_2 emissions in millions of metric tons (Mt) due to productive and consumptive activities in the given region. Scaling and dividing this number by total GDP yields a measure of emissions intensity measured in tons per million dollars of GDP which is reported in the final column of Table 2. The EIA reports this metric to be roughly 300 tons per million dollars of GDP for the aggregate United States in 2016.[21] On average (across sectors), New York is relatively cleaner per dollar of GDP from other composite regions in our analysis and the average across the United States.

Table 2: Aggregate regional economic data

	Total GDP (Bill. $)	**Elec VA (% of GDP)**	**Elec Demand national/state (%)**	**Total CO_2 (Mt)**	**CO_2 intensity (ton/ Mill. $)**
NY	1472.4	0.5	18.0	167.9	114.0
RGGI	1534.5	0.5	29.8	224.1	146.0
PJM	5343.3	0.9	20.5	1678.5	314.1
RUS	10350.0	0.9	5.5	3423.0	330.7

Table 3 reports electricity production by power technology. For each region, we report the percent share of total electricity production attributed to each generating technology along with associated CO_2 emissions from the given technology type. Note that CO_2 emissions are only associated with coal, oil and natural gas technologies. Relative to the total amount of CO_2 emission in New York, 16.3% stems from electricity generation. New York ranks the lowest across our model regions in the percentage of electricity

[20] Note that these shares represent recalibrated measures which reconciles BEA input output data with SEDS electricity production estimates and therefore will be slightly different than what is reported in the gross state product measures.

[21] See: https://www.eia.gov/todayinenergy/detail.php?id=30712. The country wide average in our constructed dataset is 294 tons per million dollars of GDP.

generation attributed to fossil fuel-based production (50%) and highest in the share of renewable generation exclusive of nuclear (21%).

Table 3: State-level electricity generation

		Generating Technologies							
		Coal	*Oil*	*Gas*	*Nuclear*	*Hydro*	*Geo*	*Solar*	*Wind*
NY	% Generation	1.5		48.5	28.7	18.5		0.1	2.7
	CO_2 (Mt)	1.5		25.8					
RGGI	% Generation	16.4	0.9	48.6	27.5	4.2		0.6	1.8
	CO_2 (Mt)	17.5	0.4	26.6					
PJM	% Generation	46.4	0.5	27.9	22.0	1.3		0.3	1.6
	CO_2 (Mt)	518.8	2.0	130.0					
RUS	% Generation	33.1	1.2	41.3	10.8	6.4	0.5	0.9	5.9
	CO_2 (Mt)	701.2	11.1	365.4					

4. Policy Analysis

In this section, we numerically assess the environmental and economic impacts of imposing an additional overlapping carbon policy in New York. In order to understand these impacts, we first generate a *Business-As-Usual* (BAU) baseline by solving the model to reflect current RGGI carbon pricing. This procedure for imposing the existing regulatory environment in the model adjusts the reference carbon emission quantities on the power sector across both New York and other RGGI states to satisfy a price target of \$5 per metric ton of CO_2.[22] Table 4 illustrates the difference between the benchmark data reported in the previous section and our computed BAU baseline. BAU levels reflect reference assumptions as laid out in the previous section and Appendix A.

Table 4: Benchmark data (Ref.) versus. business-as-usual (BAU) baseline

		NY		RGGI	
		Ref.	BAU	Ref.	BAU
Carbon Price (\$/tCO2)		0	5	0	5
Ele. Technology	Coal	1.5	1.4	17.5	16.2
Emissions (tCO2)	Gas	25.8	24.8	26.6	25.5
	Oil			0.4	0.3

[22] From here to the end of the analysis, any reference to RGGI states does not include New York. New York is treated as separated as described in the data section.

Our carbon adder scenarios target an exogenously set social cost of carbon by assigning additional costs to electricity generators equal to the difference between the desired SCC and the RGGI carbon price (initially calibrated to the BAU). Notably, this difference is endogenously determined within the model as the RGGI carbon price adjusts depending on market conditions. We also impose an explicit price floor constraint for the RGGI carbon price in accordance with its regulatory design. One potential mechanism for carbon reductions in the RGGI regions with a self-imposed cap on emissions is to drive the price of permits low enough to warrant adjustments in the carbon cap. The model endogenously reduces the carbon emissions cap in RGGI regions if permit prices fall below \$2.15 per ton of CO_2 (recent revisions to the RGGI program adjusted the reserve price to \$2.15 per short ton of CO_2 (RGGI, 2016)). We provide computed impacts (all defined as being relative to the BAU) for social cost of carbon estimates ranging between \$1 - \$50 per ton of CO_2. Additional carbon revenues generated in these scenarios are recycled lump sum back to households.[23]

Figure 4 reports the changes in the RGGI carbon price for the range of potential social cost of carbon estimates set by New York and the associate change in the emissions cap in the market to maintain the price floor. The figure contrasts the difference between the simulated price level and the potential boundaries in the regulatory environment (BAU and price floor).

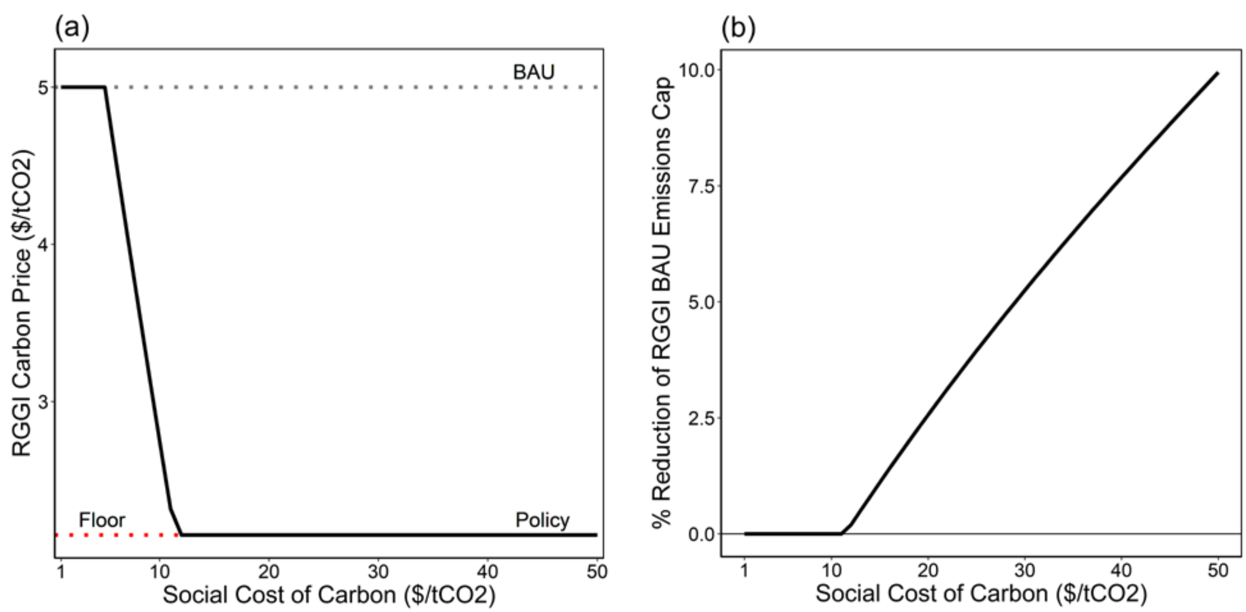

Figure 4: RGGI price level (a) and emissions cap adjustments (b)

[23] There are various ways to revenue recycling, such as returning revenue to households, load-serving entities, etc. Each of these will give rise to different price, resource utilization and leakage impacts. In our analysis, we use the recycling scheme where carbon adder revenue is transferred back to households in a lump-sum fashion.

As laid out in the partial equilibrium analysis of Section 2, an additional carbon adder policy on top of the pre-existing RGGI cap and trade market drives down the RGGI carbon price. Note that when the social cost of carbon is set between \$1 - \$5 per ton of CO_2, the RGGI cap on emissions represents the binding constraint in New York. In these cases, the BAU model solution match the policy equilibrium. For SCC estimates set greater than \$5/tCO_2, the RGGI price decreases from \$5/tCO_2 to the price floor. Once the RGGI carbon permit price reaches the price floor at \$2.15/tCO_2, the emissions cap in the RGGI market is adjusted to maintain the price at \$2.15/tCO_2. Setting the social cost of carbon in New York to \$42/tCO_2 in line with the New York Public Service Commission recommendations, the emissions cap would need to be lowered by 5.6 million tons, or 8.1% of the BAU emissions cap to remain at the price floor.

The main driver of the decrease in the RGGI price is the decrease in the aggregate demand for RGGI allowances. This is mainly due to a changing electricity generation composition, and to a smaller extent, a scale effect on NY's power sector. CO_2 pricing on NY's conventional power generation disincentives coal and gas-based generation significantly (New York does not have oil based production in the benchmark for this year). In the baseline, cost-effectiveness is assured by the equalization of marginal abatement costs across the CO_2 emitters within the RGGI regions (including New York). By creating a gap between abatement prices at the margin for NY and RGGI power generators, a carbon adder generates excess economic cost for the NY generators under a binding RGGI cap. Figure 5 reports the percent change in electricity generation by aggregate technology type relative to the BAU. Aggregate technology types are characterized as black (fossil fuel emitting technologies) and green (all other technologies). At the recommended social cost of carbon by the NYPSC (\$42/tCO_2), New York electricity production falls by 10.3%. Broken down by technology types, electricity generation by green technologies increases by 0.8%, and decreases for black technologies by 21.6%. This reduction in black electricity production by disaggregate technology type depends on the carbon intensity of the technology: at \$42/tCO_2, coal based electricity production is reduced by 45.2%, while natural gas based electricity production is reduced by 20.9% (noting that natural gas production makes up 97% of fossil fuel based electricity production in the state). Despite the slight positive scale effect on green technologies, these two effects combine to decrease the aggregate demand for RGGI allowances from electricity producers in New York, driving down the RGGI permit price.

While the complementary carbon adder policy disincentivizes dirty generation technologies in New York, it has the potential to impact electricity production in other regions through trade and existing regulations. The remainder of Figure 4 describes changes to the composition of electricity generation due to the unilateral policy in New York. The carbon adder policy has the opposite effect in other RGGI states.

Before the permit price reaches the price floor, black electricity production increases in response to falling permit prices. This change is driven by large increases in coal-based generation in the region. When the permit price reaches the price floor (the social cost of carbon in New York is set to \$12/tCO_2), coal-based electricity production increases by 3.5%, gas-based production increases by 1.6%, and oil-based production increases by 1.1%. Notably, green production decreases slightly in response to falling permit prices in other RGGI states. Thereafter, with a fixed price per ton of CO_2, changes in regional production levels is in response to terms of intra-national trade and reductions in New York's level of electricity production.

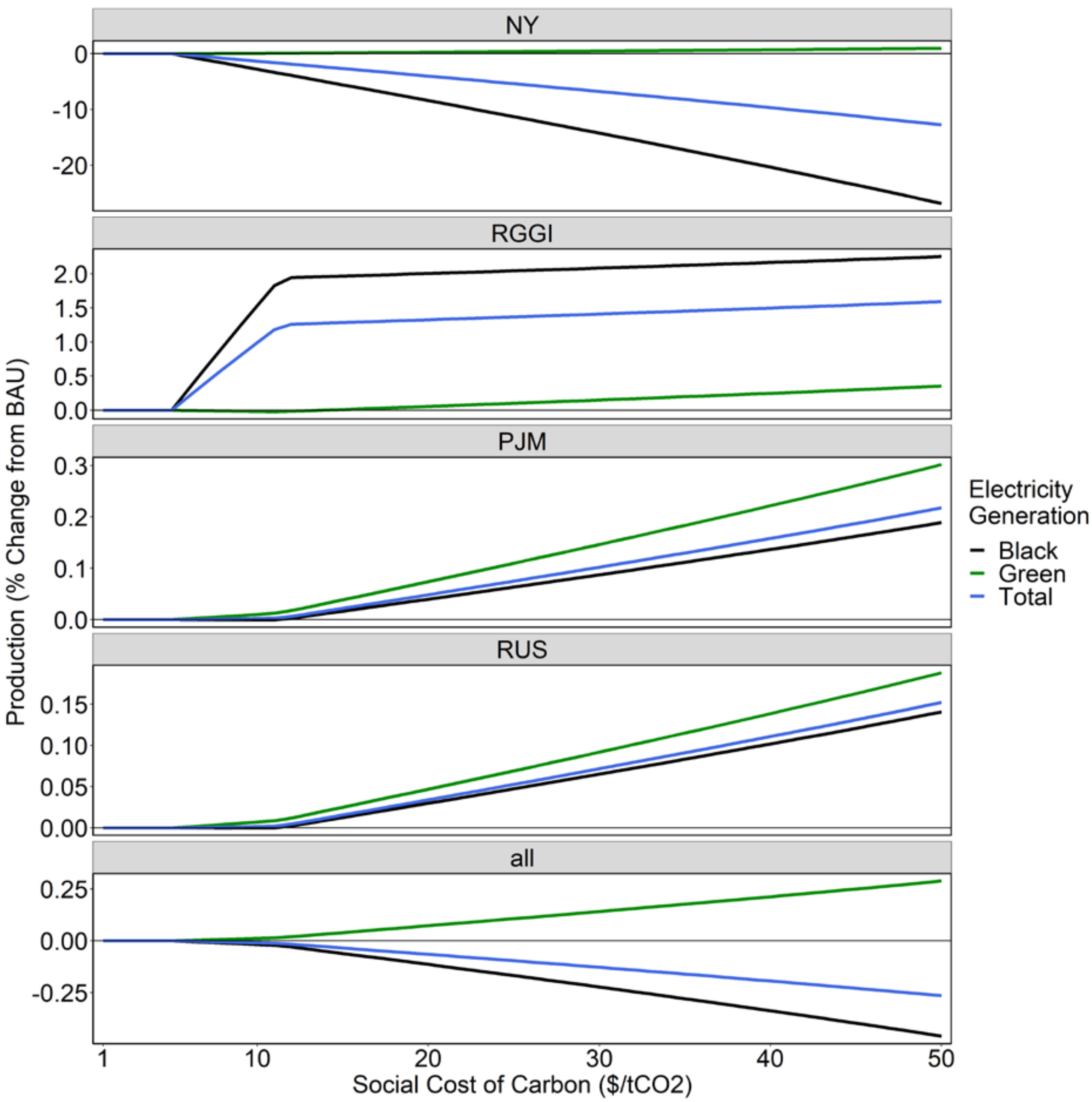

Figure 5: Percentage change in electricity generation w.r.t. BAU by aggregate technology

The impacts on other regions in the model such as PJM and the rest of the United States (RUS) are modest. In both cases, neither region is effectively regulated by carbon policies. Increases in electricity output is due to increased trade between RGGI states and New York. Aggregated across all regions in the model, the final panel of Figure 4 reports the impact of the policy across the United States by aggregated generating technology. The reductions in black generating technologies in New York more than compensates for increases in RGGI states and in other areas to generate small decreases at the national level.

The changes in composition and scale of electricity generation (together with induced general equilibrium cross-market spillover effects) lead to changes in aggregate carbon emissions reported in Table 5 (reported at the NYPSC recommended level of \$42/tCO_2). Implementing a carbon adder on the electricity sector in New York produces a 4.6% decrease in economy-wide state-level emissions. [24] The carbon adder policy forces New York based generators to pay for additional CO_2 abatement. Fossil fuel-based generation in the RGGI states gain cost advantage over greener generation technologies, observed most significantly in the coal-based generation, which is the most CO_2-intensive generation technology. This leads to an overall increase in RGGI's CO_2 emissions. However, the increases in both RGGI states and the rest of the United States does not fully eclipse decreases in New York, i.e. US emissions slightly decrease by 0.05%. Changes to electricity trade flows into and out of a given state are provided in the next two columns of Table 5. Electricity exports from New York fall by 17% while electricity imports increase by 15%. The increase in imports is composed of electricity exports from the other regions. The net effect is to make the electricity sector across the United States modestly cleaner. One metric considering the cost of this transition is given in the final column, measured as the percent change in gross state product. The cost is largely born by New York with small decreases elsewhere in the economy.

Table 5: Macroeconomic Impacts (SCC = \$42/tCO_2)

	CO2 (% Change)	**Ele. Out (% Change)**	**Ele. In (% Change)**	**GDP (%) Change**
NY	-4.6	-17.3	15.5	-0.02
RGGI	0.7	5.3	-0.4	-0.002
PJM	0.1	0.8	-0.6	-0.003
RUS	0.1	1.4	-1.3	-0.002
all	-0.05	0	0	-0.003

[24] This does not include co-pollutants of electricity generation. Local levels of ambient air pollution could change because of this policy. This is beyond the scope of the current study.

Figure 6 reports the impacts to the end-user price of electricity (solid) in New York (blue) and RGGI states (green). Clear enough, electricity price impacts depend on the exogenously set social cost of carbon. At a social cost of carbon set to \$42/tCO_2, end-user electricity prices in New York increases by 0.7%. In other RGGI states, the electricity price decreases by 0.01% up to when the permit price reaches the price floor, and then increases given trade with other regions and a fixed permit price. Trade serves to mitigate the price impacts, particularly in the New York region. In that case, excess domestic demand is met by increased electricity imports from other states, which eventually contributes to the moderate increase in NY's end-user price of electricity. While NY becomes a net electricity importer, the RGGI region becomes a net electricity exporter, with an increase in its electricity exports on the order of 5.3%. The black line represents a weighted average of electricity price impacts across the United States. The interconnectivity of NY and all other RGGI states via electricity trading has a significant impact on how the carbon adder policy affects the electricity output and final electricity prices.

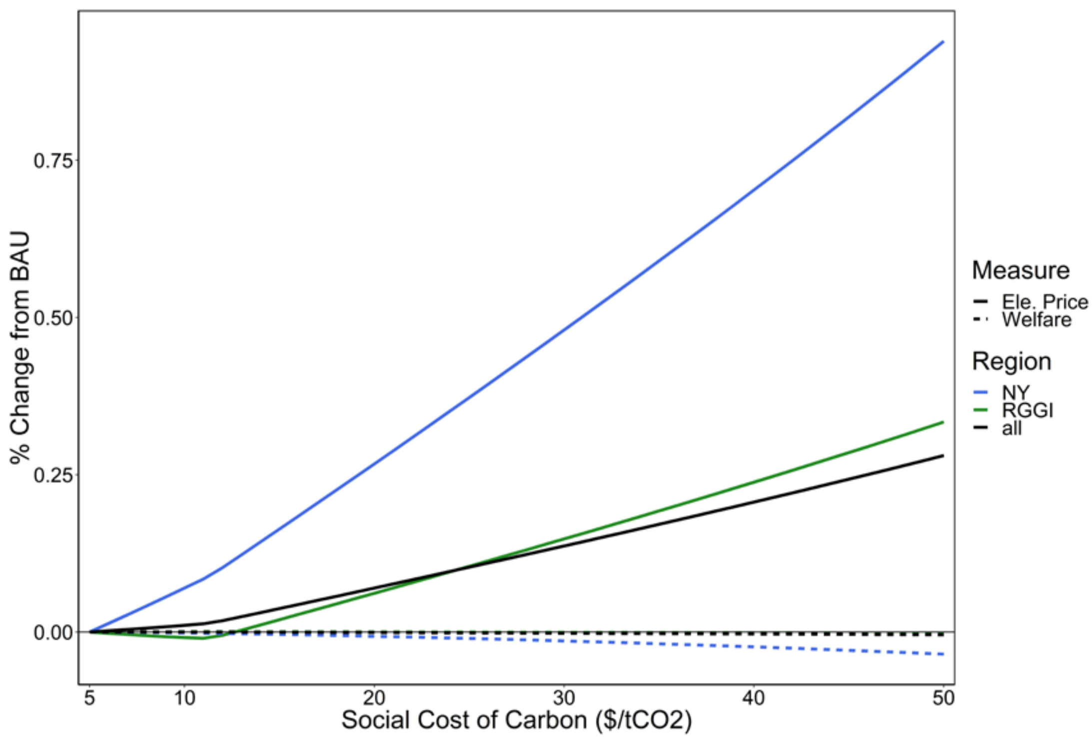

Figure 6: Percent change in end-user electricity price and equivalent variation w.r.t. BAU

Changes to electricity prices impact household welfare. Figure 6 also reports the percent change in equivalent variation relative to the baseline (dotted line) for both New York and RGGI states. We note that equivalent variation is an imperfect measure of welfare in this case as it does not include willingness to pay for carbon abatement or other co-benefits/costs that may be a result of the policy (local levels of emissions). This metric does, however, characterize the loss in welfare due primarily to changes in the electricity price. The loss in NY's economic welfare is around 0.03% under \$42/tCO_2. On the other hand, decreasing CO_2 allowance prices due to freed up allowances lead to small welfare improvements for the RGGI region up to when the price hits the price floor. Afterward, small welfare losses are computed (-0.002% at \$42/tCO_2). Note that this metric is only reported for a single representative agent in each model region. While aggregate impacts are small, there may be significant heterogeneity in household impacts depending on household-specific characteristics such as income.

The reported results reflect our reference assumptions on elasticities as listed in Appendix A which drive price-responsive reactions to policy shocks on the supply and demand side. Sensitivity analysis reveals in particular the importance of supply elasticity values governing the fixed-factor production technologies (coal, crude oil, natural gas, and electricity generating technologies). Table 6 details the difference between our reference outcomes as reported above and sensitivities which either halved (Low) or doubled (High) the assumed supply elasticities at the recommended social cost of carbon. Note that the top-level substitution elasticity which governs the tradeoff between the fixed factor and a Leontief composite of all other inputs depends proportionally on the assumed supply elasticity.[25] A larger top-level elasticity embeds additional price sensitivity in the model. In both states, national exports and imports and aggregate CO_2 emissions increase in absolute value from lower to higher elasticities. Macroeconomic impacts (welfare and GDP) changes remain modest. The RGGI permit price hits the price floor when the social cost of carbon is set to \$42/tCO_2 irrespective of the range of elasticities tested in sensitivity.

Table 6: Supply elasticity sensitivity on aggregate outcomes (SCC = \$42/tCO_2)

	New York			RGGI		
	Low	**Ref.**	**High**	**Low**	**Ref.**	**High**
End-user Electricity Price (%)	0.5	0.7	0.9	0.2	0.3	0.3
Subnational Electricity Exports (%)	-11.9	-17.3	-23.1	3.2	5.3	8.4
Subnational Electricity Imports (%)	10.0	15.5	22.2	-0.2	-0.4	-0.9
Welfare (%)	-0.018	-0.026	-0.034	-0.001	-0.002	-0.001
GDP (%)	-0.012	-0.016	-0.020	-0.002	-0.002	-0.001
CO_2 (%)	-3.0	-4.6	-6.6	0.4	0.7	1.4
Carbon Price (\$/tCO_2)	42	42	42	2.15	2.15	2.15

[25] Letting η denote the assumed supply elasticity and θ be the fixed factor value share, we calibrate the substitution elasticity, σ, to be equal to: $\sigma = \eta\theta/(1-\theta)$.

Figure 7 describes the production responses by electricity generating technology type across the range of supply elasticities explored in sensitivity. The reference case described above is characterized by the bolded lines, while the sensitivity simulation produces a range of impacts described by the dotted (Low) or dashed (High) lines. Reducing the supply elasticities on electricity generation generates smaller output responses to imposed cost of carbon estimates. However, this trend does not hold true in coal-based electricity production in New York, where increasing the social cost of carbon past \$44/tCO_2 results in a complete reduction in production. When the elasticity is small, inflexibilities in production make coal (the dirtiest technology in New York) too costly as a feasible technology type competing to supply electricity in the area when the cost of carbon is set high enough. [26]

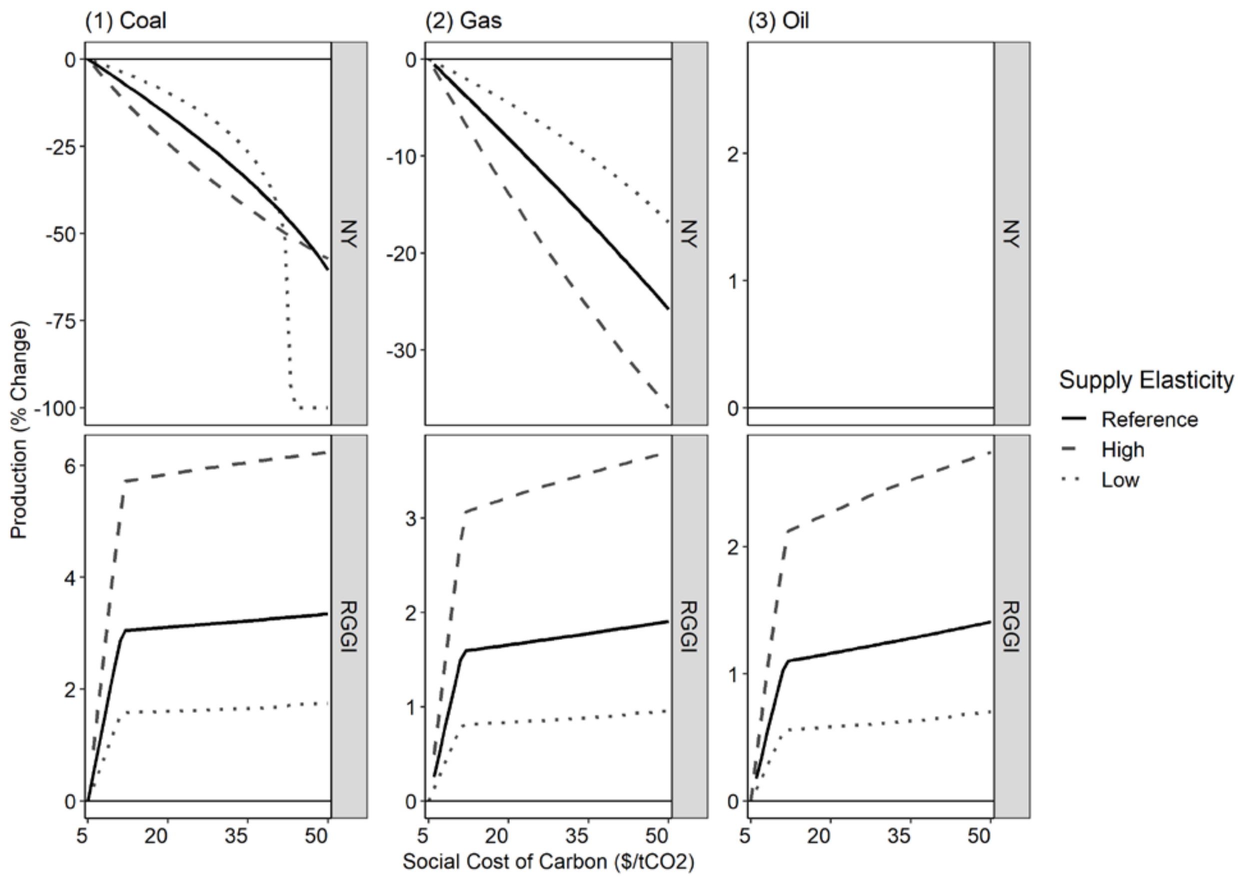

Figure 7: Electricity generation sensitivity (supply elasticity)

[26] We also conducted sensitivities on our assumed Armington elasticities of substitution for electricity and energy intensive production to understand the importance of trade in the model. Doing so produced very little substantive differences in model results. The only noticeable difference were electricity price impacts. Reducing the Armington elasticity for electricity generated larger price impacts (by roughly half an additional percentage point at \$42/tCO_2).

5. Conclusions

In its latest State Energy Plan, New York committed itself to reduce its economy-wide greenhouse gas emissions by 40% below 1990 levels by 2030, with the most significant contribution planned to come from the power sector, i.e. 50% of electricity stemming from renewable sources by 2030. New York has adopted market-based carbon pricing on its power sector through the Regional Greenhouse Gas Initiative (RGGI) since 2009 which so far is the only effective carbon pricing instrument in the state. However, the RGGI price has been low for the past decade despite the revisions on its overall cap and is expected to cause New York to fall short of its State Energy Program targets.

As a complementary instrument, New York is considering additional carbon pricing for its power generators, in the form of a carbon-adder targeting the environmental externality generated from power generation. This aims to help New York's power generators truly internalize the cost of generating CO_2 emissions, to accelerate the reduction of state-wide CO_2 emissions and to ease the transition to the renewable resources by giving these industries cost advantage over the high emission intensive generation units. From the sole perspective of climate policy, however, supplementing a cap-and-trade program with additional carbon pricing options outside the program is likely to create additional costs since this induces "excessive" emission abatement from the expansion of renewable energy and drives a price wedge between the power sectors that are subject to RGGI pricing.

In this paper, we have used a numerical model of the U.S. economy represented at the sub-national level to substantiate basic economic intuition with quantitative evidence on the additional costs of overlapping regulation in the case of New York. Any unilateral climate action, taken as a complementary action to the RGGI program, has the potential to induce downward pressure on the RGGI price. Under a binding RGGI cap, this leads to the reallocation of emissions and market shares across the RGGI states, while not providing any environmental mitigation gains. However, our analysis revealed the importance of the price floor mechanism in the RGGI market, which induces carbon permit retirements. The potential emission leakage to the other RGGI states might lead to local or regional pollution outside of New York as well. Our simulations also indicate that imposing additional CO_2 pricing on top of the RGGI pricing can lead to economic losses in NY and to a smaller extent, nearby states. Therefore, if the objective of the New York's State Energy Plan is to generate ambitious emissions reductions in a cost-effective manner, it needs to consider interactions with the RGGI program.

While our numerical model captures the fundamental cost and market implications of unilateral carbon pricing in the RGGI region, it oversimplifies some of the complex real-world relationships and market dynamics which might be topics for future more refined research. In the current study, we made simplifying assumptions on RGGI market dynamics with the inclusion of a price floor. The emission containment reserve (ECR) mechanism, which will be implemented in 2021, might be a much more effective policy tool in addressing the potential for downward pressure on the RGGI price under carbon adder policy (RGGI, 2017). An ECR is envisioned as an additional mechanism to the reserve price, which will dynamically adjust the supply of emission allowances according to the allowance price even when the price is above the price floor. If the allowance demand is low, then the market clearing price is expected to fall. If the market price falls to the minimum as prescribed by the ECR, then some amount of allowances associated with the ECR would not be sold and the allowance price would eventually respond to the reduced supply. By definition, an ECR can be designed to have multiple price steps, which gives the RGGI states the ability to design upward sloping allowance supply curves. This way the potential carbon adder policy, as well as any other unilateral pricing policy, might be used to meet more ambitious emission targets. Our analysis shows that the right design of an ECR mechanism can help manage some of the excess cost and leakage impacts of overlapping regulation. Additionally, the current set of simulations have a simplistic representation of the electricity generating sector and do not have dynamic market adjustment to allowance prices, such as the explicit treatment of investment in lowest/non-emitting technologies, energy efficiency and conservation technologies, which might provide further improvements in the cost figures.

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Appendix A: Algebraic model summary

A competitive equilibrium is characterized by three conditions in our model: producers earn zero economic profits, markets must clear and incomes balance with expenditures. We formulate our computable general equilibrium model in a mixed complementarity framework. Activity levels are complementary to zero profit conditions and prices are determined through clearing markets. Let Π_{rs}^{u} denote a unit profit function of sector *s* (aliased with goods *g*) in region *r*, where *u* denotes the assigned name to the production activity. Discrete power generation indices are embedded in the sectors and commodities index (as are a composite household good *c*, government public good *g* and aggregate investment *i*). Through Hotelling's lemma, differentiating the profit function with respect to prices yields compensated supply and demand coefficients which are used to concisely represent market clearance conditions. We let *FE* denote the subset of *s* representing fossil fuels and *EG* the subset representing all primary energy goods (coal, crude oil, and natural gas) and discrete electricity generation technologies.

Tables A.1 – A.6 explain the notations for variables and parameters employed within our algebraic exposition. Substitution possibilities between inputs of production are differentiated depending on whether a sector is non-extractive (Figure A1) or subject to fixed factors of production (such as primary fuel production or discrete electricity generation technologies – Figure A2).

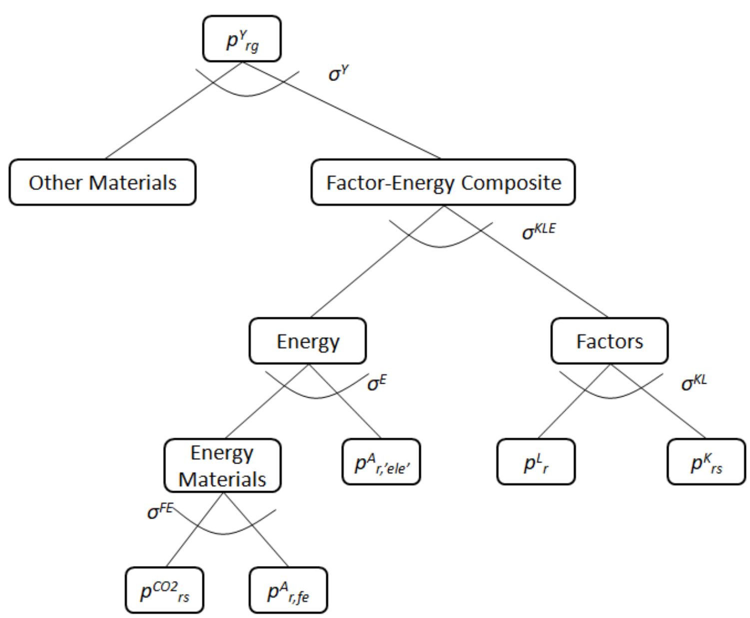

Figure A1: General production structure (KLEM)

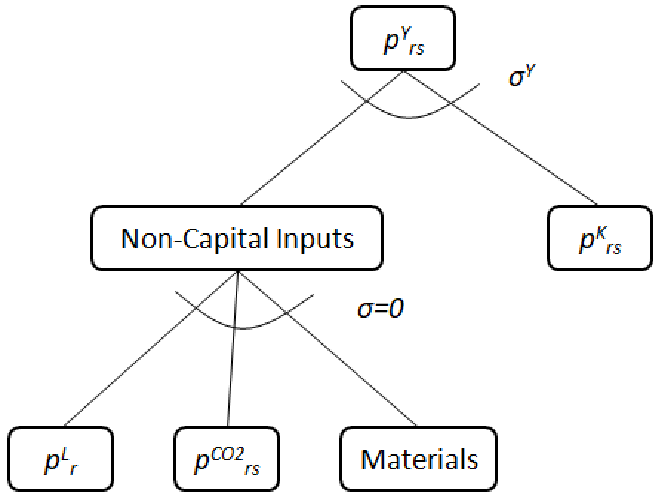

Figure A2: Fixed factor production

<u>Zero profit conditions</u>

1. Production of goods except energy goods ($s \notin EG$):

$$\Pi_{rs}^{Y} = p_{rs}^{Y} - \left[\theta_{rs}^{MAT} p_{rs}^{MAT^{1-\sigma_{rs}^{Y}}} + (1-\theta_{rs}^{MAT}) p_{rs}^{KLE^{1-\sigma_{rs}^{Y}}}\right]^{\frac{1}{1-\sigma_{rs}^{Y}}} \le 0$$

2. Sector- and region-specific materials aggregate ($s \notin EG$):

$$\Pi_{rs}^{MAT} = p_{rs}^{MAT} - \left[\sum_{g} \theta_{rsg}^{M} p_{rg}^{A^{1-\sigma_{rs}^{M}}}\right]^{\frac{1}{1-\sigma_{rs}^{M}}} \le 0$$

3. Sector- and region-specific aggregate of value-added and energy inputs ($s \notin EG$):

$$\Pi_{rs}^{KLE} = p_{rs}^{KLE} - \left[\theta_{rs}^{VA}\left(\theta_{rs}^{L} p_{r}^{L^{1-\sigma_{rs}^{KL}}} + (1-\theta_{rs}^{L}) p_{rs}^{K^{1-\sigma_{rs}^{KL}}}\right)^{\frac{1-\sigma_{rs}^{KLE}}{1-\sigma_{rs}^{KL}}} + (1-\theta_{rs}^{VA}) p_{rs}^{E^{1-\sigma_{rs}^{KLE}}}\right]^{\frac{1}{1-\sigma_{rs}^{KLE}}} \le 0$$

4. Sector- and region-specific energy aggregate ($s \notin EG$):

$$\Pi_{rs}^{E} = p_{rs}^{E} - \left[\theta_{rs}^{\mathrm{ELE}} p_{r,ELE}^{A^{1-\sigma_{rs}^{E}}} + \left(1-\theta_{rs}^{\mathrm{ELE}}\right)\left(\sum_{g\in FE} \theta_{rgs}^{FE}\left(p_{rg}^{A} + p_{r}^{CO2} a_{g}^{CO2}\right)^{1-\sigma_{rs}^{FE}}\right)^{\frac{1-\sigma_{rs}^{E}}{1-\sigma_{rs}^{FE}}}\right]^{\frac{1}{1-\sigma_{rs}^{E}}} \le 0$$

5. Production of primary fuels and discrete power generation ($s \in EG$):

$$\Pi_{rs}^{Y} = p_{rs}^{Y} - \left[\theta_{rs}^{Q} p_{rs}^{K\,1-\sigma_{rs}^{Y}} + \left(1-\theta_{rs}^{Q}\right)\left(\theta_{rLs}^{FQ} p_{r}^{L} + \sum\nolimits_{g} \theta_{rgs}^{FQ}\left(p_{rg}^{A} + p_{r}^{CO2} a_{g}^{CO2}\right)\right)^{1-\sigma_{rs}^{Y}}\right)^{\frac{1}{1-\sigma_{rs}^{Y}}} \leq 0$$

6. Transformation of domestic production:

$$\Pi_{rg}^{X} = \left[\theta_{rg}^{FX} p^{FX\,1+\eta_{rg}^{X}} + \theta_{rg}^{NX} p_{g}^{N\,1+\eta_{rg}^{X}} + \theta_{rg}^{D} p_{rg}^{D\;1+\eta_{rg}^{X}}\right]^{\frac{1}{1+\eta_{rg}^{X}}} - p_{rg}^{Y} \leq 0$$

7. Armington aggregate:

$$\Pi_{rg}^{A}$$
$$= \left(1-t_{rg}^{A}\right) p_{rg}^{A}$$
$$-\left[\sum\nolimits_{m} \theta_{rgm}^{MAR} p_{m}^{MAR} + \theta_{rg}^{G}\left(\theta_{rg}^{FG}\left(\frac{\left(1+t_{rg}^{M}\right) p^{FX}}{\overline{p^{FX}}}\right)^{1-\sigma_{rg}^{FAR}} + \left(1-\theta_{rg}^{FG}\right) p_{rg}^{DG\,1-\sigma_{rg}^{FAR}}\right)^{\frac{1}{1-\sigma_{rg}^{FAR}}}\right] \leq 0$$

8. Domestic goods demand:

$$\Pi_{rg}^{DG}$$
$$= p_{rg}^{DG}$$
$$-\left[\theta_{r,rg}^{DG} p_{rg}^{D\;1-\sigma_{rg}^{NAR}} + \left(\sum\nolimits_{rr} \theta_{r,rr,g}^{DG} p_{rr,g}^{D\;1-\sigma_{rg}^{NAR}}\right) 1(g \in \{ELE\}) + \theta_{Nrg}^{DG} p_{g}^{N\,1-\sigma_{rg}^{NAR}} 1(g \notin \{ELE\})\right]^{\frac{1}{1-\sigma_{rg}^{NAR}}}$$
$$\leq 0$$

9. Margins:

$$\Pi_{m}^{MAR} = p_{m}^{MAR} - \sum\nolimits_{rg} \theta_{rgm}^{MS}\, p_{rg}^{Y} \leq 0$$

<u>Market clearance conditions</u>

10. Labor:

$$\overline{L_{r}} \geq \sum\nolimits_{s} Y_{rs} \frac{\partial \Pi_{rs}^{Y}}{\partial p_{r}^{L}}$$

11. Capital:

$$\overline{K_{rs}} \geq \sum\nolimits_{g} Y_{rg} \frac{\partial \Pi_{rg}^{Y}}{\partial p_{rs}^{K}}$$

12. Output:

$$\sum\nolimits_{s} Y_{rs} \frac{\partial \Pi_{rs}^{Y}}{p_{rg}^{Y}} + \overline{Y_{rg}} \geq \ X_{rg} \frac{\partial \Pi_{rg}^{X}}{\partial p_{rg}^{Y}}$$

13. Armington aggregate:

$$A_{rg} \geq \sum\nolimits_{s} Y_{rs} \frac{\partial \Pi_{rs}^{Y}}{\partial p_{rg}^{A}}$$

14. Regional goods:

$$X_{rg} \frac{\partial \Pi_{rg}^{X}}{p_{rg}^{D}} \geq A_{rg} \frac{\partial \Pi_{rg}^{A}}{\partial p_{rg}^{D}}$$

15. National goods:

$$\sum\nolimits_{r} X_{rg} \frac{\partial \Pi_{rg}^{X}}{\partial p_{g}^{N}} \geq \sum\nolimits_{r} A_{rg} \frac{\partial \Pi_{rg}^{A}}{p_{g}^{N}}$$

16. Foreign exchange:

$$\sum\nolimits_{r} \overline{FE_{r}} + \sum\nolimits_{rg} X_{rg} \frac{\partial \Pi_{rg}^{X}}{p^{FX}} \geq \sum\nolimits_{rg} A_{rg} \frac{\partial \Pi_{rg}^{A}}{p^{FX}}$$

17. Margins:

$$M_{m} \geq \sum\nolimits_{rg} A_{rg} \frac{\partial \Pi_{rg}^{A}}{p_{m}^{MAR}}$$

18. Investment (*g=i*):

$$\sum\nolimits_{s} Y_{rs} \frac{\partial \Pi_{rs}^{Y}}{p_{rI}^{Y}} \geq \overline{I_{r}}$$

19. Carbon emissions:

$$\overline{CO2_r} \geq \sum\nolimits_s Y_{rs} \frac{\partial \Pi_{rs}^{Y}}{\partial p_r^{CO2}}$$

Income Balance

20. Household budget:

$$HH_r = \sum\nolimits_g p_{rg}^{Y} \overline{Y_{rg}} + p_r^{L} \overline{(L_r - U_r \overline{u_r}) +} \sum\nolimits_s p_{rs}^{K} \overline{K_{rs}} - p^{FX} TAU_r$$

21. Government budget:

$$GOV_r = p^{FX} \overline{FE_r} + p_r^{CO2} \overline{CO2_r} + p^{FX} TAU_r + \sum\nolimits_g (t_{rg}^{A} p_{rg}^{A} A_{rg} + t_{rg}^{M} p_{rg}^{M} A_{rg} \frac{\partial \Pi_{rg}^{A}}{\partial p_{rg}^{M}})$$

Auxiliary Constraints

22. Wage curve (*s=c*):

$$\log\left(\frac{p_r^{L}}{p_{rC}^{Y}}\right) = \epsilon_r \log(U_r)$$

23. Equal governmental yield (*s=g*):

$$GOV_r = p_{rG}^{Y} \overline{Y_{rG}}$$

Table A.1: Sets and indexes

s,g	Indexes for sectors and goods
r,rr	Indexes for regions
m	Index for margins (trade and transport)
EG	All energy goods: Coal, crude oil, natural gas and electricity
FE	Primary fossil fuels: Coal, crude oil, and natural gas

Table A.2: Activity, income and auxiliary variables

Y_{rs}	Production in region *r* in sector *s*
A_{rg}	Armington composite in region *r* for good *g*
X_{rg}	Aggregate exports in region *r* for good *g*
M_m	Margin supply of type *m*
GOV_r	Government income in region *r*
HH_r	Household income in region *r*
TAU_r	Endogenous lump sum payment in region *r*
U_r	Rationing unemployment multiplier in region *r*

Table A.3: Price variables

p_{rg}^{Y}	Output market price in region *r* for good *g*
p_{rs}^{MAT}	Composite intermediate material demand price in region *r* in sector *s*
p_{rs}^{KLE}	Composite value added and resource price in region *r* for sector *s*
p_{rs}^{E}	Composite energy price in region *r* for sector *s*
p_{rg}^{A}	Armington aggregate price in region *r* for good *g*
p_{rg}^{D}	Regional market price in region *r* for good *g*
p_{g}^{N}	National market price for good *g*
p_{rg}^{DG}	Domestic demand price in region *r* for good *g*
p^{FX}	Foreign exchange rate
p_{r}^{L}	Wage rate in region *r*
p_{rs}^{K}	Rental rate of capital in region *r* for sector *s*
p_{m}^{MAR}	Margins price for type *m*
p_{r}^{CO2}	CO_2 emissions price in region *r*

Table A.4: Cost shares

θ_{rs}^{MAT}	Cost share of material inputs in production for region *r* in sector *s*
θ_{rsg}^{M}	Cost share of good *g* in sector *s* for region *r* in the MAT aggregate
θ_{rs}^{VA}	Cost added cost share in region *r* in sectors *s* in the KLE aggregate
θ_{rs}^{L}	Cost share of labor in the value added nest in region *r* in sector *s*
θ_{rs}^{ELE}	Cost share of electricity in the energy aggregate in region *r* in sector *s*
θ_{rgs}^{FE}	Cost share of fossil fuels in the energy aggregate in region *r* for good *g* in sector *s*
θ_{rs}^{Q}	Cost share of capital in energy production in region *r* for sectors *s*
θ_{r*s}^{FQ}	Cost share of non-capital inputs in energy production in region *r* for sector *s* and input *
θ_{rg}^{FX}	Value share of foreign exports in region *r* for good *g*
θ_{rg}^{NX}	Value share of national exports in region *r* for good *g*
θ_{rg}^{D}	Value share of regional exports in region *r* for good *g*
θ_{rgm}^{MAR}	Cost share of margins in the Armington aggregate in region *r* for good *g* and type *m*
θ_{rg}^{G}	Cost share of foreign and domestic goods in the Armington aggregate in region *r* and good *g*
θ_{rg}^{FG}	Cost share of foreign goods in the goods aggregate in region *r* and good *g*
θ_{r*g}^{DG}	Cost share of domestic goods in the domestic goods aggregate in region *r* for good *g* and location *
θ_{rgm}^{MS}	Value share of margin supply in region *r* for good *g* and type *m*

Key: KLE – value-added and energy; MAT – materials; MAR – margins.

Table A.5: Elasticities

η_{rg}^{X}	Transformation between foreign and domestic export supply	4 (set to 16 for s∊{ele})
σ_{rs}^{Y}	Substitution between the materials and KLE composites ($s \notin EG$)	0.25
σ_{rs}^{Y}	Substitution between capital and other inputs in fossil fuel production calibrated to exogenous supply elasticities μ_{FE} ($s \in EG$)	$\mu_{COL} = 2.4, \mu_{CRU} = .15, \mu_{GAS} = .5, \mu_{et} = .5$
σ_{rs}^{M}	Substitution between materials goods in production	0
σ_{rs}^{KL}	Substitution between value added components in production	1
σ_{rs}^{KLE}	Substitution between value added and energy in production	0.25
σ_{rs}^{E}	Substitution between electricity and fuel types in production	0.5
σ_{rs}^{FE}	Substitution between fuel types in production	0
σ_{rg}^{FAR}	Armington substitution between foreign and a domestic composite	2 (set to 16 for s∊{ele})
σ_{rg}^{NAR}	Armington substitution between domestic demand sources	4 (set to 16 for s∊{ele})

Table A.6: Endowments and emissions coefficients

$\overline{L_r}$	Aggregate labor endowment in region *r*
$\overline{K_{rs}}$	Aggregate capital endowment in region *r* and sector *s*
$\overline{Y_{rg}}$	Household production in region *r* of good *g*
$\overline{FE_r}$	Foreign exchange endowment in region *r*
$\overline{I_r}$	Investment demand in region *r*
$\overline{CO2_r}$	CO_2 emissions in region *r*
a_g^{CO2}	CO_2 emissions coefficient for good *g*
t_{rg}^A	Tax rate on Armington demand in region *r* on good *g*
t_{rg}^M	Tax rate on imports in region *r* on good *g*

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