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Carbon Emissions Forensic in Energy Sector: Is It worth the effort?

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Abstract

Climate policy has mostly focused on regulating power suppliers. Suppliers then reduce their greenhouse gas emissions through retrofitting pollution control devices, switching fuels, or alternating energy production processes. There is a growing interest to explore regulating emissions from the demand side by incentivizing consumers to reduce their energy consumptions or purchase power from cleaner sources through tracking carbon content of power flow in the transmission network. This paper analyzes the market outcomes under two approaches: producer-based and demand-based carbon tax. In particular, we formulate each approach as a market equilibrium model. For the consumer-based approach, we assume that a utility who procures electricity on behalf of consumers is subject to the carbon tax. For the producer-based approach, the producers will pay for their emissions. We show the two approaches are equivalent when the program's coverage is complete. That is, they produce the same prices, distribution of emissions and the economic rent allocation. However, when the coverage is incomplete, the consumer-based carbon tax is less effective in pricing carbon emissions owing to the fact that sales to unregulated nodes are not subject to the carbon tax. Given that the transaction cost of implementing consumer-based tax is likely to be higher, benefit of tracking power flows in order to estimating carbon content might not be justified even with a full coverage program.

Keywords: Climate policy; electricity industry; Carbon Tax; Linear Complementarity Problem.

1 Introduction

Incidence of climate-change policy is of great interests to economists, policymakers, and the power sector. Market-based instruments, such as pollution tax, renewable energy credit, or cap-and-trade programs, rely on internalizing pollution costs to motivate changes in investments or operations in the energy sector. Those instruments are mostly imposed on the producers whose behavior is consistent with profit-maximizing principle. When incorporating pollution costs, producers will favor cleaner technologies.

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Consumers can also be subject to market-based instruments such as a volumetric energy tax on gasoline. The gas tax, in principle, will fully account for pollution costs associated with the life-cycle of gasoline from extraction to final consumption. When consumers refill gas, a high energy tax will discourage consumers to forgo trips that are not essential or less valuable, thereby decreasing driving mileage. Those behavior changes are induced by a clear price signal that inform consumers making rational choices. With the advance in information technologies, such as smart meter and home management system coupled with smart-phone system that allow consumers receive real- or nearly real-time market data, there has been growing interests in demand-side policy intervention in order to reduce energy consumptions in the power sector.

Power engineers who concern about climate change also explore ways allowing for explicitly identifying the carbon footprint of the system flow so as to design a fair scheme to assign responsibility to the end-users. Examples include ? that propose a network-based approach to associate the carbon intensity to consumers located at different buses using proportional sharing theorem. ? develop a carbon flow tracing method in order to determine the carbon accounting at the regional level and locational carbon intensity assessment at the user level. ? propose a way to trace carbon emission flow while considering emission associated with transmission losses by allocating them to the end-users. Ultimately, the goal is to using the information from those flow tracking methods to put a price tag on the end-users to reflect their carbon footprints. In fact, a number of emerging programs, e.g., UK Carbon Reduction Commitment Energy Efficiency Scheme, the Tokyo Emission Trading Scheme, India Perform Achieve and Trade, the energy obligation is directly placed to the large end-users, and those end-users are allowed to trade energy saving certificates or emission allowances ?.

These policies that focus on emission reduction through sending a price signal directly or bypass producers to the end-users are likely to be inefficient for a number of reasons. First, transaction cost is expected to be high as there are many more consumer entities than a handful of producers so the monitoring cost or the verification effort could be a concern. Second, practically the existing billing system by utilities is already complicated, making it difficult, especially for residential consumers to react. Even the policy is efficiently implemented where the transaction cost is minimized, as shown in this paper, with the complete coverage, the market outcomes will be equivalent to the ones when producers are subject a carbon tax. That is, either producers or consumers are subject to a tax will lead to the same prices, same quantity demanded, and same distribution economic rent when the revenue from the carbon tax received by the government is properly accounted for. As the monitoring cost or the verification effort is likely to be less with a smaller number of producers than the end-users, our analysis suggests that regulating producers might be a more effective way to reduce emissions in the energy sector. Finally, when the program is partial covered with some power sales are exempted from the carbon tax, a consumer-based regulation will be less effective in pricing carbon emissions.

To understand the equivalence of market outcomes under different point-of-regulation, we begin our analysis in Section 2 with a graphic approach to illustrate the impacts of the electricity price and the rent distribution when either the producers or consumers are subject to a carbon tax. We then review in Section 3 the relevant literature to highlight the contribution of the paper. While the graphic approach herein allows for establishing equivalence of the market outcomes in a simple case, it does not account of some essential features of the electricity market, including transmission network, heterogeneity of technologies, grid operator, and independent system operator. Our analysis then develop more

detailed models that account the aforementioned factors in Section 4. Detailed model is then applied to the regional energy market in Section 5. Conclusions is then summarized in Section ??.

2 Graphic Analysis: Beyond Tax Incidence

It is well known that the incidence of tax depends on the elasticity of demand and supply. In general, the higher the price elasticity of demand, the greater the burden on producers; reversely, the higher the price elasticity of supply, the greater the burden on consumers. Beyond the tax incidence, economists are also interested in market outcomes when an exercise tax, either on the purchase or sale of a good, is imposed on a commodity. Figure 2 illustrates the impacts of a carbon tax (T^{CO_2}) on the energy sector with consideration of a linear supply (S) and a linear demand curve (D). The equilibrium pair of quantity and price in absence of a tax is given by Q_E and P_E , respectively. Assuming that the price increases to P_C when implementing a tax on the *consumers* for their energy consumption, this suggests that quantity demanded by the consumers is equal to Q_T , while the price received by the producers is P_P . The difference between P_C and P_P represents the carbon tax, T^{CO_2} , levied by the government. The tax revenue collected by the government is therefore equal to $Q_T \times T^{CO_2}$. The consumer surplus falls by the sum of the area A+B; the producers surplus declines by the sum of the area C+K. The total surplus will be shrunk by only the area of B+K (a deadweight loss) owing to the tax revenue A+C. The deadweight loss is then offset by the avoided carbon damage. If the the avoided carbon damage is exactly equal to B+K, the policy is efficient in this simple case.¹

Alternatively, producers can be subject to a carbon tax T^{CO_2} for their energy production with CO_2 emission as by-product. This is equivalent to shifting the supply curve (S) up by the tax amount of T^{CO_2} to the curve S' . In this case, the equilibrium price will be P_C , while the producers need to surrender a total tax of A+C to the government. As a result, the decrease of the consumers surplus and the producers surplus is equal to the area of A+B and C+K, respectively. When accounting for the revenue received by the government or A+C, the total surplus owing to the carbon tax is B+K. This simple *partial equilibrium* analysis illustrates the fact when the market is perfectly competitive, the point-of-regulation, either producers or consumers, will not alter the market outcomes. Of course, the situation is much more complicated when the endogenous interactions are accounted for in a general equilibrium framework.

3 Literature Review

The incidence of climate change policy is of great interests to economists. For example, using the Consumer Expenditure Survey and an augmented input-output model of the US economy, work by ? show that a carbon tax on CO_2 emission is regressive, implying that it has a disproportional impact on the low-income households. ? apply a input-output analysis to examine the impact of changing to a GHG-based tax from a CO_2 -based tax in the UK economy. The paper finds that GHG-based tax would lower marginal abatement cost, lessen the incidence of low-income households by shifting the burden away from the

¹In reality, the pre-existence of other taxes, such as an income tax, might interact with the carbon tax or the permit and create further distortion, leading to welfare loss, see for example ?.

Figure 1: Impact of Carbon Tax on Market Outcomes

food products. Those paper go beyond analyses of a single sector models and allow the impacts of a tax through supply-demand flows among different sectors.

Another stream of research focuses on the single sector and studies the pass-through of the CO₂ to the price of electricity in the energy sector. Pass-through of CO₂ permit price depends on a number of factors, e.g., market structure, merit-order changes, price and demand elasticity. In general, the pass-through is negatively (positively) related to the electricity market demands (supplys) price responsiveness. If the electricity market demand is not price-responsive, the pass-through is expected to be close to 100%. In contrast, a highly price-responsive electricity market supply likely results in a pass-through of close to 0% (?) .

Using a simulation-based approach, ? examine the pass-through and windfall profits at early phase of EU ETS. The study concludes that nearly all the windfall profits are associated with the lump-sum allowance rent through the initial allocation while the pass-through rates are 60–100% for Dutch markets and 60–80% for German markets. Study by Wild et al. (2015), using a agent-based modeling, finds AN incomplete pass-through for the Australian National Energy Market, especially for the region with substantial hydro generation. Empirically, with available historical market data, various studies have assessed *ex post* the CO₂ prices pass-through. For instance, ? investigate the windfall profit in early stage of EU ETS; ? find that rising CO₂ prices of EU ETS permits have a stronger impact on wholesale electricity prices than falling CO₂ prices (asymmetric effect); ? document that a 1% increase in the CO₂ price leads to a 0.32% increase in electricity prices in the European market; ? conclude an nearly 100% pass-through in Spain. More recently, ? estimates a pass-through of 84%–104% in Germany. Finally, a statistically insignificant pass-through also is found by ? when studying the second phase of the EU

ETS.

A number of papers examine the market outcomes when the power sector is subject to C&T policies that differ by their point-of-regulation. ? analyzes a form of downstream CO₂ regulation in the electricity sector that requires retail suppliers to buy energy from a mix of sources so as to satisfy a emission standard. The paper finds that the so-called “downstream” regulation neither solves emissions leakage, nor leads to a less procurement cost for consumers, or provides more incentive for energy efficiency than the traditional cap-and-trade program. ? study the three carbon emissions trading programs for the electric power sector considered by the California government under the AB32: load-based, source-based and first-seller. The paper shows that “emission leakage” eliminates most of the emissions reductions that the regulations attempt to impose. Further, “contract reshuffling” occurs to such an extent that all the apparent emissions reductions resulting from changes in sources of imported power are illusory.

With a growing interest in reducing emissions by regulating consumers behavior through taxation, our contribution to the existent literature is to illustrate that the carbon emissions forensic in energy sector by associating carbon content with consumers is *not* necessary as an equivalent tax levied on the producers would lead to the same market outcomes when the coverage is complete. While this principle is well known in a simple case as alluded to in the graphic analysis, we establish the equivalence in market outcomes with consideration of several essential physical and institutional aspects of the electric market, including transmission network, grid operator, heterogeneous technologies, and ownership of multiple firms.

4 Models

We present the detailed models within this section. Section 4.1 gives the problem faced by the grid operator. The grid operator’s problem is commonly shared by both the producer- and consumer-based regulation models. Models of the producers and consumers under the producer- and consumer-based regulation are presented in Sections 4.2 and 4.3, respectively. Together with the market clearing conditions, those conditions constitute a complementarity problem, which define the equilibrium of the market. We begin with the grid operator’s conditions that are commonly shared with two scenarios followed by the producers and joint problem faced by the utility and consumers. For each problem, we then derive the corresponding first-order conditions.

4.1 Grid Operator

Grid Operator/Independent System Operator The system operator allocates scarce transmission capacity among demands for transmission services:

$$\begin{aligned} & \underset{y_{it}}{\text{maximize}} && \sum_{i,t} w_{it} y_{it} \\ & \text{subject to} && -T_k \leq \sum_i PTDF_{ki} y_{it} \leq T_k, (\lambda_{kt}^-, \lambda_{kt}^+) \quad \forall k, t, \end{aligned} \tag{1}$$

where y_{it} is the the amount of power delivered from the hub to node i by the operator. (Note that y_{it} can be negative when the power flow is in the reverse direction from node i to the hub.) We use the direct-current approximation to derive power transfer distribution factors (PTDFs) to represent load flows in the network (e.g., Schweppe et al., 1998). The constraint associated with the grid operator is that the total flow has to be not more than the upper bound for interface k based on thermal or other limits, T_k .

The firstorder conditions for the grid operator's problem (1) is defined as follows:

$$0 \leq \lambda_{kt}^+ \perp \sum_i PTDF_{ki} y_{it} - T_k \leq 0 \quad (2)$$

$$0 \leq \lambda_{kt}^- \perp - \sum_i PTDF_{ki} y_{it} - T_k \leq 0 \quad (3)$$

$$w_{it} + \sum_k PTDF_{ki} (\lambda_{kt}^- - \lambda_{kt}^+) = 0. \quad (4)$$

4.2 Producer-based Regulation

Consumers Consumers' demand for power at node j in period t is represented by the inverse demand function:

$$p_{jt}^E = P_{jt}(Q_{jt}), \quad \forall j, t. \quad (5)$$

Nodal consumption is equal to $Q_{jt} = \sum_{f,i,h \in H_{if}} x_{fihjt}$, where x_{fihjt} is the quantities sold to node j from the power plant h owned by producer f with $P_{jt}'^E < 0$ and $P_{jt}''^E \leq 0$.

Producers We assume that the bulk sales of power are in the form of bilateral contracts between producers and consumers. Producer f maximizes its profit in (6) by determining output level x_{fihjt} of plant h located at node i that sell to node j :

$$\text{Maximize}_{x_{fihjt}} \sum_{j,t} (p_{jt}^E - w_{jt}) \left(\sum_{i,h \in H_{if}} x_{fihjt} \right) - \sum_{t,i,h \in H_{if},j} (C_{fih}(x_{fihjt}) - w_{it}x_{fihjt} + T^{CO2} E_{fih} x_{fihjt}) \quad (6)$$

$$\text{subject to} \quad \sum_j x_{fihjt} \leq X_{fih}, (\rho_{fih}) \quad \forall i, h \in H_{if}, t, \quad (7)$$

$$\forall x_{fihjt} \geq 0.$$

The term $p_{jt}^E - w_{jt}$ in the objective function is the per unit revenue, in which the producer sells $\sum_{i,h \in H_{if}} x_{fihjt}$ of power to consumers at node j at given price p_{jt} , while paying for the transmission charge w_{jt} to the grid operator to bring power from the network hub to consumers. The term $C_{fih}(x_{fihjt}) - w_{it}x_{fihjt} + T^{CO2} E_{fih} x_{fihjt}$ is the total cost of producing power from plant h at node i , where $C_{fih}(x_{fihjt})$ is the variable generation cost and $-w_{it}$ is the price charged by the transmission operator to bring power from node i to the hub, and $h \in H_{if}$ denotes the power plant owned by producer f at node i . We assume that $C_{fih}' > 0$ and $C_{fih}'' \geq 0$. The last term $T^{CO2} E_{fih} x_{fihjt}$ is incurred emission cost with T^{CO2} and E_{fih} denoting the permit price and the emission rate, respectively.

In addition to non-negativity restrictions, producers have two types of constraints. The first constraint states that power generation (left-hand side) and sales (right-hand side) have to balance during each period. The second constraint indicates that the output generated, $\sum_j x_{fihjt}$, is not greater than its derated generation capacity X_{fih} .

The first-order conditions of the producer's problem under the producer-based regulation is expressed as follows:

$$0 \leq x_{fihjt} \perp (p_{jt}^E - w_j) - C_{fih}' + w_{it} - T^{CO2} E_{fih} - \rho_{fih} \leq 0 \quad (8)$$

$$0 \leq \rho_{fih} \perp \sum_j x_{fihjt} - X_{fih} \leq 0. \quad (9)$$

Market Clearing Condition One condition is essential to calculating a market equilibrium. The condition is associated with power transmission to ensuring balance of the physical system, with the wheeling fee, w_{it} , implicitly defined.

$$\sum_{f,i,h \in H_{if}} x_{fihjt} - \sum_{f,h \in H_{jf}} x_{fjh} = y_{jt}, \quad \forall j, t, \quad (10)$$

The set of conditions (2)–(3), (5), (8)–(10) defines the market equilibrium of the producer-based regulation.²

4.3 Consumer-based Regulation

Consumers/Utility We assume that a utility or load-serving entity, who procures the electricity on half of consumers through bilateral contracts with producers, will be the entity in compliance with the regulation. We therefore model the problem faced by the consumers and the utility jointly in i -th location as follows:

$$\begin{aligned} & \text{Maximize}_{z_{fihjt}} \sum_t \int_0^{d_{it}} p_{it}^E(q) dq - \sum_{j,f,t} p_{fjh} z_{fjh} - T^{CO_2} E_{fjh} z_{fjh} \\ & \text{subject to} \quad z_{fjh} \geq 0, \quad \forall j, h \in H_{jf}, t. \end{aligned} \quad (11)$$

A utility decides the amount of power, z_{fjh} , to procure from power plant in j node owned by firm f through a bilateral contract while subjecting to a carbon tax. Its total sale is d_{it} , which is equal to $\sum_{f,j,h \in H_{jf}} z_{fjh}$. The term p_{fjh} is the bilateral settlement price between the utility i and the firm owning the facility, which is exogenous to the utility's problem, but endogenously determined by the model. The price paid by the consumers, p_{it}^E , will be equal to the settlement price p_{fjh} plus the emission cost $T^{CO_2} E_{fjh}$.

The corresponding first-order conditions of the joint optimization problem faced by the consumers and the utility is displayed as follows.

$$0 \leq z_{fjh} \perp p_{it}^E - p_{fjh} - T^{CO_2} E_{fjh} \leq 0 \quad (12)$$

Producers Under the consumers-based regulation, the producer's problem needs to be modified by eliminating T^{CO_2} term from the objective function (6). This yields the revised problem as follows:

$$\text{Maximize}_{x_{fihjt}} \sum_{j,t} (p_{fih} - w_{jt}) x_{fihjt} - \sum_{t,i,h \in H_{if}} (C_{fih}(x_{fihjt}) - w_{it} x_{fihjt}) \quad (13)$$

²The theoretical properties of the resulting complementarity problem, including existence and uniqueness of the solutions, can be found in ? and ?. In general, with a quadratic objective function and linear constraints so that each entity's problem is with a unique solution, there exists a unique solution to the overall equilibrium problem.

$$\begin{aligned} \text{subject to } \sum_j x_{fihjt} &\leq X_{fih}, (\rho_{fih}) \quad \forall i, h \in H_{if}, i, t, \\ x_{fihjt} &\geq 0, \quad \forall i, h \in H_{if}, j, t. \end{aligned} \quad (14)$$

The first-order conditions of the producer's problem under the consumer-based regulation is expressed as follows:

$$0 \leq x_{fih} \perp (p_{fih} - w_j) - C_{fih} + w_{it} - \rho_{fih} \leq 0 \quad (15)$$

$$0 \leq \rho_{fih} \perp \sum_j x_{fihjt} - X_{fih} \leq 0 \quad (16)$$

Market Clearing Condition Two conditions are essential to calculating a market equilibrium. These conditions associated with power transmission to ensuring balance of the physical system (17) as well as to equating the offer and the purchase quantities in the bilateral transactions with the settlement prices, p_{fihjt} implicitly defined by equation (18).

$$\sum_{f,i,h \in H_{if}} x_{fihjt} - \sum_{f,h \in H_{if},j} x_{fihjt} = y_{jt}, \quad \forall j, t, \quad (17)$$

$$x_{fihjt} = z_{fihjt}, \forall i, f, h \in H_{if}, j, t. \quad (18)$$

The collection of conditions (2)–(4) and (14)–(18) define the market equilibrium under the consumer-based regulation.

4.4 Equivalence of Consumer- and Producer-based Regulation

As alluded to in Section 2, the two regulations differed by their point-of-regulation, one by consumers in Section 4.3 and one by producers in Section 4.2, are equivalent in theory. To see this, we assume that $x_{fihjt} = z_{fihjt} > 0$ for all $i, f, h \in H_{if}, j, t$. Eq. (12) implies that $p_{jt}^E = p_{fihjt} + T^{CO2}E_{fih}$ or $p_{fihjt} = p_{jt}^E - T^{CO2}E_{fih}$. In other words, the bilateral settlement price paid by the utility to producers, p_{fihjt} , equals the price paid by the consumers, p_{jt} , minus CO₂ tax, $T^{CO2}E_{fih}$. Had a producer owned a zero-emitting power plant, it will be fully compensated by the price paid by the consumers. Otherwise, it will incur emission tax, $T^{CO2}E_{fih}$, that needs to surrender to the government. If we substitute the term $p_{fihjt} = p_{jt}^E - T^{CO2}E_{fih}$ with p_{fihjt} in Eq (15), and replace all the z_{fihjt} with x_{fihjt} , two sets of the first-order conditions will be equivalent. This establishes the equivalence of the two regulations differed by their point-of-regulation, i.e., consumers and producers.³

5 Numerical Case Study

The joint optimization problems faced by consumers, producers and the grid operator can be simultaneously solved by taking the first-order conditions for each of the problems. The collection of each entity's optimization problem together with the market-clearing condition, forming a complementarity problem, collectively defines the market

³In case when some x_{fihjt} (or z_{fihjt}) equal to zero, one can insert a slack variable to equating the RHS of Eq. (12), and the same approach can be applied to show the equivalence.

equilibrium. We illustrate the equivalence of the market outcomes under the consumer- and producer-based regulation by solving the model using PJM (Pennsylvania-Jersey-Maryland) regional electric market data. PJM market serves a good case study because that the Regional Greenhouse Gas Initiative has been implemented since 2009. We study two cases: a consumer-based tax and a producer-based carbon tax. We describe the background of PJM market in Section 5.1, the data in Section 5.2, the calibration in Section 5.3, followed by the numerical results in Sections 5.4–??.

5.1 PJM Regional Power Market

Fig.2 displays the geographic coverage and network of the electricity market simulated in the model. It covers six states, including Maryland, New Jersey, Pennsylvania, West Virginia, Delaware and Virginia as well as Washington, DC.⁴ The market is represented by seventeen power control areas (utilities) and twenty-four transmission lines. Each power control area is a load center at which load serving entities procure electricity on behalf of their customers. Several control areas are split into more than one node for better representation of congestion pattern. The network represents the transmission system above 500 kV lines.⁵ The flow in the network is modeled by the linearized of direct-current (DC) flow approximation based on Kirchoff Laws (Schweppe et al., 1988). The required information such as reactance and thermal capacity of transmissions lines is obtained from PowerWorld, which is based on FERC (Federal Energy and Regulatory Commissions) Form 715. The peak demand in 2012 in the model was approximately 70 GW, representing approximately 50% of the load in the current PJM RTO.

5.2 Data & Assumptions

The main data source for generation characteristics (e.g., capacity, heat rate, emissions rates, fuel costs, etc.) is from SNL with supplementary data obtained from EPA eGRID. The capacity is derated based on forced-outage rate to reflect unanticipated plant outages, using data from GADS (Generation Availability Data System) maintained by NERC. (North American Reliability Corporation). The states' capacity mix varies considerably. Table 1 summarizes the states' generating capacity by fuel types. The total installed

⁴The PJM Interconnection market was first established in 1999, providing electricity to consumers residing in Maryland, New Jersey, Pennsylvania, Delaware and the District of Columbia. Since then, its footprint has evolved considerably. In particular, Rockland and Allegheny Energy joined in 2002, and three utilities, including Commonwealth Edison, American Electric Power and Dayton Power & Light, joined the PJM in 2004. Duquesne Light and Dominion Virginia joined the the PJM in 2005. PJM is further expanded to include American Transmission Systems and Cleveland Public Power in 2011, Duke Energy Ohio and Duke Energy Kentucky in 2012, and East Kentucky Power in 2013. Today, the PJM RTO (regional transmission organization) covers 13 states and DC, serving 65 million customers with the peak load equal to 143 GW.

⁵Further changes were made to model the nodes encompassing with more than one state. In particular, we split a node into two if the initial node contains two states. We assume that the baseline power quantity demanded is in proportion to the generation capacity of the state within the node. Two states, then, are connected with a transmission line with a unlimited transfer capacity. The topology of the additional nodes to the initial system will be radial so the augmented network adds no extra loops. Three nodes are augmented, including ME2 (New Jersey and Pennsylvania), PS (New Jersey and Pennsylvania), and WV (West Virginia and Pennsylvania). (The states within the parenthesis representing the those within that node.) The augmented network contains twenty-seven arcs and twenty-two nodes. These splits are necessary as we are interested in the impact of the market outcomes when the rather polluting state, i.e., Pennsylvania, becomes subject to the carbon tax in Section ??.

Figure 2: PJM Regional Power Market Transmission Network

derated capacity is 124 GW in our model. Four states—Pennsylvania, Virginia, New Jersey and West Virginia—account for more than 85% of the total installed capacity for the market simulated in the study. West Virginia has more than 85% of coal capacity due to its abundant coal; in contrast, coal accounts for less than 12% for New Jersey. For Maryland and Pennsylvania less than 40% of the capacity is coal, followed by natural gas plants, while natural gas accounts for more than 70% of capacity in Delaware.

Table 1: State capacity by fuel type [MW] in Study Region

Fuel	MD	NJ	PA	DE	VA	WV	DC
Coal	5127	2139	17296	804	5742	13984	0
Gas	2369	11574	12673	2467	8498	1211	0
Nuclear	1829	4181	10015	0	3654	0	0
Others	0	453	1541	0	3109	0	0
Oil	3300	1310	2954	83	2738	18	755
Renewables	640	42	1646	10	954	750	0
Total	13265	19699	46125	3364	24695	15963	755

The simulation period is year 2012, comprising 8784 hours. Yearly load is represented by nine periods: permutation of three seasons (i.e., summer, winter and spring/fall) and three periods (i.e., mid daytime, morning/evening and night). Unlike NEMS (National Energy Modeling System), which defines summer as from June to September, we include May in the summertime in order to model ozone season. The size of the blocks varies from 455 to 1683 hours. The allowance prices of the CAA Title IV SO₂ and NO_x CAIR programs are assumed to be \$2.5 and \$17/t, respectively.⁶ These values are based on

⁶The price of both the SO₂ trading program under the CAA (Clean Air Act) IV as well as EPA's CAIR program of the NO_x permits has declined drastically since 2007. For example, SO₂ stood at a \$500 per short ton in 2007, slipped to \$300 in 2008 and dropped to slightly above \$2 in 2011 while the price of the NO_x CAIR permits declined from \$800 in 2008 to \$16 in 2011. Those dramatic changes are

2011 data reported by EIA. For our analysis, we assume a CO₂ of \$15/t. While this price is significantly higher than the historical market value, our interest is *not* to predict or to duplicate the market prices but to explore the market outcomes under different policy settings.

5.3 Calibration

During 2012, the RGGI CO₂ permit price was reported to bounce around 2–3\$/ton. We assume a CO₂ permit price of \$3/ton in our baseline. Our baseline simulation did a reasonably good job in matching the overall average price of the PJM but with a greater dispersion of power prices among nodes. The baseline simulated price of the entire PJM is 34.1 \$/MWh, which is slightly higher than the historical data of 33.1 \$/MWh. Overall, our simulation grossly under-estimates the total emission (aggregated over all the states) by a margin of 3% or 7 million tons. Figure 3 plots the simulated baseline CO₂ emission against the reported historical data. Each point represents a state sample. If the simulated ones perfectly predict the actual emissions, the sample points will fall on the 45-degree dash line. If sample points lie above (below) the 45-degree line, it indicates a over-estimate (a under-estimate). Overall, the baseline simulation does a great job in estimating CO₂ emissions from Maryland, New Jersey, Delaware, but underestimates Pennsylvania’s emissions while overestimating emission from other states. This is partially because our generating dataset does not include some power plants located in western Pennsylvania.⁷

However, we are less concerned about our calibration as our intention, instead of predicting market outcomes, is to illustrate what might happen had a carbon tax been imposed on either the consumers or the producers. Thus, rather than arbitrarily adjusting the fuel costs, the variable O&M or other parameters, we decide to go with the current dataset and focus on *qualitative* difference when comparing the results under different cases.

5.4 Main Results

Table 2 presents the main results of the analysis when the coverage is complete. The table contains three parts, where the upper part gives the prices, the total sales, the regulated CO₂ and the emissions; the middle part displays the social surplus outcomes; the lower part breaks the CO₂ by states. The row “regulated CO₂” represents the amount of emissions that is priced by the carbon tax. The three columns (1)–(3) correspond to cases of the consumer-, the producer-based regulation and the baseline, respectively.

Consistent with the conclusions in Sections 2 and 4, policies with different point-of-regulation will lead to the same market outcomes when the coverage of regulation is complete, and the markets are competitive, i.e., columns (1)–(2). The same sale-weighted prices, the total emissions and other aggregated market outcomes are reported in two cases. The producer surplus, ISO’s revenue (congestion rent) and the government tax, which is calculated as the tax multiplied with the total emissions, are equivalent between

in response to the uncertainty of the program as the District of Columbia Court of Appeals was in favor of the State of North Carolina by striking down CAIR in July 2008 . Even when the court reinstated the program temporarily in the following December until the EPA could finalize a replacement plan, with certain restrictions were put on the implementation, the market has essentially collapsed since then.

⁷The generating inventory in our analysis excludes those power plants within the territory of American Electric Power, American Transmission Systems and Duquesne Light due to data limitations.

Figure 3: Plot of simulated emissions of baseline Case (carbon tax (permit) =3 \$/ton) against CEMS reported emissions in 2012.

two cases. As the consumer-based regulation is formulated as a "joint" optimization problem faced by the utility and consumers, the consumers surplus is represented by the surplus earned by the utilities, which is equal to the consumers surplus in the producer-based scenario. Comparing to the baseline, a complete coverage of the carbon tax directly deter power outputs from more high-polluting sources, especially power plants located in Pennsylvania and West Virginia. The shrink in power supply is partially compensated by increasing output from relatively low-emitting sources in Maryland. Only 29.7×10^6 tons of CO_2 (or 13%) is priced by the carbon tax at the baseline compared to a 100% under the full coverage. The full coverage of the carbon tax also elevates the power prices by a margin of 38% and suppresses power demand by $5 \times 10^6 \text{MWh}$.

When a carbon tax is applied only to a subset of the nodes within an inter-connected regional power market, the equivalence between the consumer- and producer-based will not likely to hold. This is mainly because only the sales destined to a node, which is subject to the policy, incur the carbon cost while other sales are exempted from the carbon tax. We assume only those nodes associated with states that are part of the current RGGI will be subject to a carbon tax in order to examine the impact of consumer and producer-based policy on the market outcomes under the incomplete coverage. Under this assumption, a total of four nodes, i.e., BGEPEP, BGE2, DPL, and APMD, associated with Maryland, DC, and Delaware will be subject to the carbon tax, while other nodes are exempted from the tax.

Tables ??-?? report the outcomes under the partial or incomplete coverage. Tables ?? gives the market-related variables, and Table ?? displays the state-specific power price and CO_2 emissions. A number of observations emerge from the table. First, in comparison

Table 2: Results of the Consumer- and Producer-based Regulation under the Complete Coverage and Baseline

Point of Regulation	Consumers (1)	Producers (2)	Baseline (3)
Sale-weighted Price [\$/MWh]	47.05	47.05	34.1
Total CO ₂ [10 ⁶ tons]	218.5	218.5	225.2
Regulated CO ₂ [10 ⁶ tons]	218.5	218.5	29.7
Total Sales [10 ⁶ MWh]	429.9	429.9	434.7
Producer Surplus [M\$]	7,471.9	7,471.9	4,398.4
Consumer Surplus [M\$]	NA	324,780.0	330,372.2
ISO Revenue [M\$]	849.9	849.9	978.1
Government [M\$]	3,277.0	3,277.0	89.12
Utility [M\$]	324780.0	NA	NA
Social Surplus [M\$]	336,379.4	336,379.4	335,837.9
Maryland ^{a,b}	21.67	21.67	20.86
New Jersey ^a	14.97	14.97	15.90
Pennsylvania ^a	62.59	62.59	74.32
Delaware ^{a,b}	4.41	4.41	4.27
Virginia ^a	30.72	30.72	28.47
West Virginia ^a	79.53	79.53	76.77
DCa, bs	4.58	4.58	4.58

^a: denote states subject to carbon tax in cases (1) and (2).

^b: denote states subject to carbon tax in baseline (3)

to the producer-based regulation (left) the sale-weighted price is lower by 4 \$/MWh while the total CO₂ emission is higher under the consumer-based policy by 5.2×10^6 tons. This is mainly because under the producer-based regulation, only the sales to those regulated states will incur a carbon cost. In other words, exports from those regulated states to other “unregulated” states will be exempted from the carbon tax. On the other hand, all the generation within the “regulated states” is subject to the tax under the producer-based regulation. In a way, the consumer-based regulation is less stringent as a utility is allowed to procure or to swap their contracts so that the import becomes less polluting so as to avoiding the carbon tax. In our simulation, without any existing contracts, utilities within the regulated states are allowed to do so to the extent to avoid the carbon tax entirely by importing zero-emitting power so that Regulated CO₂ becomes zero. In contrast, as the regulation is tied directly to the generators in the producer-based regulation, the extent that the sector can “avoid” the carbon is limited. The amassed Regulated CO₂ is roughly 14.9×10^6 tons (summation of emissions over Maryland, Delaware and DC) while the total surrendered tax is equal to \$222.8M. Second, the higher the power prices experienced in the producer-based regulation means a higher level of producer surplus by a margin of \$514M or 15% even with the carbon tax. Third, the lower power price under the consumer-based regulation benefits the consumers (jointly with the utility) by \$5,171M or roughly by 1.5%. Finally, when considering carbon tax proceedings, the social surplus under the consumer-based regulation is better off as it is less “stringent” by designs. Of course, we are fully aware of the fact that the damage caused by additional CO₂ emission (5.2×10^6 tons) should be properly accounted for when comparing social surplus under the carbon tax regulation.

Table 3: Results of the Consumer- and Producer-based Regulation under the Partial Coverage

Variables \ Regulation	Consumers (1)	Producers (2)
Sale-weighted Price [\$/MWh]	33.56	37.64
Total CO ₂ [10 ⁶ tons]	226.5	221.3
Regulated CO ₂ [10 ⁶ tons]	0	14.9
Total Sales [10 ⁶ MWh]	434.8	433.7
Producer Surplus [M\$]	1524.8	2716.4
Consumer Surplus [M\$]	NA	328,828.6
ISO Revenue [M\$]	906.7	1,444.2
Government [M\$]	0	222.8
Utility [M\$]	334,000.4	NA
Social Surplus [M\$]	336,431.9	333,211.9

Turning our attention to the power prices and the state-level emissions, producers within the regulated region when subjecting to the producer-based policy will incorporate more carbon tax in their marginal cost (compared to the production-based policy) , thereby leading to an increase in the power price. Higher power prices in regulated regions provide power plants sitting in unregulated region economic incentives to increase their exports, also leading to higher power prices. Therefore, the state-level power prices under the producer-based regulation raise by 3–25% when comparing to their counterparts under the consumer-based policy. With comparison to the consumer-based policy (1), the CO₂ emissions from regulated states under the producer-based policy (2) declines by a total of 22.0×10^6 tons. This decline is then offset by an increase of CO₂ by 16.7×10^6 tons from unregulated states, leading to an overall decrease of 5.2×10^6 tons. Overall, the CO₂ emissions tend to amass to unregulated states under the producer-based policy than that under the consumer-based regulation as the latter policy allows for contract re-arrangements so that power produced from regulated states, i.e., Maryland, Delaware and DC, can export to unregulated states without subjecting to the carbon tax.

Table 4: Results of the Consumer- and Producer-based Regulation under the Partial Coverage

State \ Regulation	CO ₂ Emissions ^b		Power Price ^c	
	Consumers (1)	Producers (2)	Consumers (1)	Producers (2)
Maryland ^a	27.91	11.63	33.41	38.23
New Jersey	15.62	16.64	40.45	42.60
Pennsylvania	72.68	80.0	34.34	35.93
Delaware ^a	4.32	0.80	37.77	39.46
Virginia	27.52	31.56	31.26	39.25
West Virginia	73.88	78.27	27.37	28.28
DC ^a	4.58	2.42	30.24	37.3

^a: denote states subject to carbon tax; ^b: emissions in [10⁶ tons] ; ^c: power price in [\$/MWh]

5.5 Sensitivity Analysis

As seen in Sections 5.4, the equivalence between the consumer- and producer-based regulation is no long held when the coverage of the regulation is incomplete. In particular, the Section 5.4 suggests that the sector can avoid the carbon tax entirely by procuring power from zero-emitting energy sources. To see that this *carbon-cost-avoidance* strategy is less likely effective when the program is expanded a greater geographic scope, especially those states with polluting sources and load centers. We perform a sensitivity by including Pennsylvania, with significant coal-fired facilities and population centers, to the RGGI program by designating additionally ME2, PE, PPL1, PPL2, PPL3, PE, PS (partial), WV (partial) and PN to be subject to the carbon tax.

Tables ??–?? report the results of the sensitivity analysis when Pennsylvania is also subject to the carbon tax. With the expansion of the carbon tax to include Pennsylvania, the consumer-based regulation is more effective in regulating emissions. Thus, the power sector cannot avoid the consumer-based regulation entirely by importing zero-emitting power to the regulated regions. A \$15/ton carbon tax is capable of regulating 17.6×10^6 tons of emissions under the consumer-based regulation, which is only less than 25% of that under the producer-based regulation, 71.1×10^6 tons. That is, there is more than 75% of carbon emissions that are “unpriced” under the consumer-based regulation. The more “extent” of incorporating the carbon tax under the producer-based regulation effectively elevates the power prices, leading to less power sales. The social surplus under the producer-based regulation, excluding benefit of 5 million tons of avoided carbon emissions, is still lower than that of the consumer-based regulation.

Table 5: Results of the Consumer- and Producer-based Regulation under the Partial Coverage with Pennsylvania

Variables \ Regulation	Consumers (1)	Producers (2)
Sale-weighted Price [\$/MWh]	37.21	43.68
Total CO ₂ [10 ⁶ tons]	225.3	220.3
Regulated CO ₂ [10 ⁶ tons]	17.6	71.0
Total Sales [10 ⁶ MWh]	433.6	431.2
Producer Surplus [M\$]	3,232.8	6,125.4
Consumer Surplus [M\$]	NA	326,228.3
ISO Revenue [M\$]	791.9	605.1
Government [M\$]	264.6	1,065.6
Utility [M\$]	332,134.4	NA
Social Surplus [M\$]	336,423.8	334,024.4

Table ?? suggests that except for the Delaware with an increase of CO₂ emission by 4.7×10^6 tons, regulated states, i.e., Maryland, Pennsylvania, DC, collectively reduce their emissions by 33.8×10^6 tons (23.6×10^6 tons reduction occurred in Pennsylvania). This is then offset by an increase of 24.1×10^6 tons emissions from unregulated states, leading to a 5×10^6 tons increase.

Table 6: Results of the Consumer- and Producer-based Regulation under the Partial Coverage with Pennsylvania

State\ Regulation	CO ₂ Emissions ^b		Power Price ^c	
	Consumers (1)	Producers (2)	Consumers (1)	Producers (2)
Maryland ^a	27.91	18.46	37.80	43.79
New Jersey	15.6	21.59	38.56	46.67
Pennsylvania ^a	72.29	48.71	43.00	44.91
Delaware ^a	4.26	8.92	36.28	46.18
Virginia	27.09	37.00	30.95	42.35
West Virginia	73.54	81.73	27.37	39.05
DC ^a	4.58	3.86	39.71	41.79

^a: denote states subject to carbon tax; ^b: emissions in [10⁶ tons] ; ^c: power price in [\$/MWh]

6 Conclusions

Climate policy has mostly focused on regulating power suppliers. There is a growing interest to explore regulating emissions from the demand side by forcing consumers to reduce their energy consumptions or purchase power from cleaner sources. One of the approaches, popular among power engineers especially, is to develop ways to track power flows in a transmission network in order to associating carbon content to the end-users' power consumption. A reliable and accurate flow tracking would lay out the foundation by which a carbon tax can be applied to regulating emissions from demand-side.

Economic theory suggests that a value-added or exercise tax on consumers would produce the same market equilibrium when the same tax is instead imposed on the producers. This paper develops market equilibrium models, one for consumer-based and one for producer-based regulation, to study these two regulations differing by their point-of-regulation. We explicitly formulate the optimization problem faced by the consumers, the producers and a grid operator interacting in a power market. A carbon tax is directly incorporated in the producers' optimization when modeling the producer-based regulation. For the consumer-based regulation, we model the problem faced by the utility and consumers as a joint optimization problem, subjecting to the carbon tax. We conclude that this equivalence principle transcends to a power market when heterogenous technologies, physical network and other more realistic considerations are accounted for. However, such equivalence is only valid if the carbon tax is applied to all generators in the power market, namely complete coverage.

With the incomplete coverage, under the consumer-based regulation, only the power sales to a regulated region will be subject to a carbon tax while sales to other non-regulated regions will be exempted from the tax. On the contrary, the producer-based regulation regulates only the producers from the regulated regions. The incomplete coverage provides economic incentives for a reliance on power imports (thereby exempting from the tax under the producer-based regulation) or contract reshuffling (thereby avoiding the tax under the consumer-based regulation) to minimize pollution cost. Those lead to the programs ineffective in regulating pollution when comparing to the complete coverage case.

We compare the performance of the two regulations when applying the models to the PJM regional market. Our analysis indicates that outcomes are mainly driven by

two effects. On the one hand, the ability to “avoid” the carbon tax under the consumer-based regulation will result in a higher level of the overall emissions. On the other hand, the more extent of regulation under the producer-based regulation (in contrast to the consumer-based regulation) will elevate the power prices, thereby encouraging emission leakage from unregulated regions. When the program is relatively less “complete”, the carbon tax is entirely avoided by utilizing contract reshuffling or relying on imports with zero-emitting power to satisfy demand under the consumer-based regulation (Table ??). In this case, the consumer-based regulation yields lower power prices as well as higher overall emissions. If the coverage is relatively complete, the greater extent of “regulation” under the producer-based regulation diminishes the ability of the sector to avoid regulation entirely through contract rearrangements, but the “effectiveness” of regulation, measured by the amount of CO₂ emissions that are priced under the tax, remains to be lower when comparing to the producer-based regulation. The social surplus comparison will be less straightforward in this case owing to the fact that the damage cost by the additional CO₂ is not accounted for.

Our analysis is subject to a number of worth-noting limitations. First, the analysis limits to the case when the power produced within regulated region exports to other unregulated regions is not subject to any regulation. In reality, policies, such as California’s AB32, can regulate in-state generation to be subject to a carbon allowance even if selling to other unregulated regions. Second, we ignore the existence of forward contracts in our analysis. As forward contracts typically account for more than 80% of power sales, the existence of forward contracts might diminish the ability of the producers or the consumers/utilities to avoid carbon costs, thereby enhancing effectiveness of the policies. However, this limitation is likely to be a short-run phenomenon as a utility might optimize their contracts to minimize their compliance cost in the long-run.

Choice of policy has a profound and long-lasting impact on the regulated industry affecting economic rent distribution among suppliers, consumers, grid operator and government. A good policy not only balances the effectiveness of the program and the incurred transaction costs but also provides correct market signals for short-run operations and long-run investment and planning. While accurately accounting for the carbon footprint using transmission flow tracking framework is seemingly appealing in theory, regulating carbon emissions through a carbon tax on power end-users might require a significant monitoring effort to ensure compliance and regulatory reform to revise tariff structure, resulting in daunting transaction cost. When the program coverage is complete, a producer-based regulation is more efficient because 1) the existing system, such as EPA Continuous Emission Monitoring System, has already been in place, and 2) the market outcomes are equal to that of the consumer-based approach. Moreover, if the program is incomplete, neither of the approaches is efficient, owing to contract reshuffling, leading to so-called emission leakage. The extent of the carbon to be priced under the consumer-based policy is expected to be smaller. Even with a more sophisticated hybrid approach designed to avoid the emission leakage, such as the first-delivery regulation with a default rate under the California AB32, the efficiency of the program remains questionable as shown by ?. For efficient regulating carbon emissions in the power sector, a program that expands beyond the local or the regional scope to cover the whole power market is needed.

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