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Carbon emission forensic in the energy sector: Is it worth the effort?

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ABSTRACT

Climate policy has mostly focused on regulating power suppliers. There is a growing interest in exploring regulating emissions from the demand side by incentivizing consumers to reduce their energy consumptions, or to purchase power from cleaner sources through tracking carbon content of power flow in the transmission network. This paper analyzes market outcomes under two approaches: producer-based and demand-based carbon taxes. We formulate each approach as a market equilibrium model. For the consumer-based approach, the analysis assumes that a utility, procuring electricity on behalf of consumers, is subject to the carbon tax. For the producer-based approach, the producers are subject to the carbon tax, and therefore, pay for their emissions. We show that the two approaches are equivalent when the program's coverage is complete. 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 regions are not subject to the carbon tax. Given that the transaction cost of implementing consumer-based tax is likely to be high, benefit of tracking power flows in order to estimate carbon content or footprint might not be justified even with a full coverage program.

1. Introduction

Incidence of climate-change policy that affects electricity production is of great interest to economists, policymakers, and the power sector. Market-based instruments, such as a pollution tax (or a Pigovian tax), renewable energy credits, 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 power producers whose behavior is consistent with the profit-maximizing principle. When incorporating pollution costs, producers will favor cleaner technologies.

Consumers can also be subject to market-based instruments, such as a volumetric or an excise energy tax for their gasoline consumption. The gas tax, in principle, will fully account for pollution costs associated with life-cycle of gasoline from extraction, production to final consumption.[1] When consumers refill gas, a high energy tax will encourage consumers to forgo trips that are not essential or less valuable, thereby decreasing driving mileages. Those behavioral changes are induced by a clear price signal that informs consumers making rational choices. With an advance in information technologies, such as smart metering and home management systems coupled with a smart-phone-type devices that allow consumers to receive real- or nearly real-time market data, there has been growing interest in demand-side policy intervention in order to reduce energy consumptions in the power sector.

With the concerns of climate change, the energy sector also is interested in exploring ways to identify carbon footprint of transmission flows in a network so as to design a fair scheme to assign responsibility to load, generators, and end-users. We refer to this in this paper as carbon forensic. Examples include Kang et al. (2015) that propose a network-based approach to associate the carbon intensity with consumers located at different buses based on a proportional sharing theorem. Rudkevich et al. (2011) define a time-variant and location specific carbon footprint as the impact of a $1/ton increase in the carbon price on the cost of serving load, transmission congestion, and generators' costs. When applying the framework to the U.S. Eastern Interconnection, the paper concludes that load is responsible for more than 100% of carbon emissions, while that of the generators is negative due to the offset of carbon emissions from wind output during off-peak periods. The carbon footprint of the transmission is also positive. While not sure how the approach can be applied to design a policy to reduce carbon emissions from the power sector, the fact that the consumers are responsible for more 100% of carbon emissions and the generators have a negative carbon footprint seems alarming. Li et al. (2013) develop a carbon flow tracing method in order to determine carbon accounting at

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[1] An energy or a gas tax could also be implemented for collecting revenue to finance transportation-related projects (Nelson, 2017).

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a regional level and to assess end-users's carbon intensity. Yang et al. (2015) propose a way to trace carbon emission flows while considering emissions associated with transmission losses by allocating them to end-users in the network. More recently, Sun et al. (2006) apply a directed-graph-based approach, an extension of Wu et al. (2000), to calculate the carbon intensity in transmission flows when thermal losses are accounted for. Ultimately, the goal is to using the information from these flow tracking methods to put a price tag on the end-users' energy consumption to reflect their contributions of carbon emissions to the system. In fact, a number of emerging programs, e.g., UK Carbon Reduction Commitment Energy Efficiency Scheme, Tokyo Emission Trading Scheme, Indian Perform Achieve and Trade, place the energy-saving obligation directly to the large end-users, and these end-users are allowed to trade energy saving certificates or emission allowances to minimize their compliance costs (Bertoldi et al., 2013).

These policies that focus on emission reductions through sending a price signal directly to the end-users are likely to be inefficient for a number of reasons. First, the transaction cost is expected to be high as there are many more individual entities compared to a handful of producers, which makes the monitoring costs or the verification effort a concern. Second, practically, the existing billing system by utilities is already complicated, making it difficult, especially for residential consumers, to react. Third, even if a policy that is efficiently implemented with a complete coverage and the transaction costs minimized, as shown in this paper, it will have market outcomes equivalent to the ones when producers are subject a carbon tax. That is, subjecting either producers or consumers to a carbon tax will lead to the same prices, the same quantity demanded, and the same distribution of economic rent when the revenue from the carbon tax received by the government is properly accounted for. This is a well-known result from microeconomics when a transmission network is not considered. (See also in Section 2 with a graph-based analysis.) As the monitoring cost or the verification effort is likely to be less with a few producers compared to a vast number of 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 partially covered with some power sales exempted from the carbon tax, a consumer-based regulation will be less effective in pricing carbon emissions. Therefore, our analysis contributes to the recent policy debates in regulating carbon emissions in the energy sector by i) formally establishing the equivalence of the consumer-based and the producer-based approaches when the coverage is complete when physical systems of the power sector are considered and ii) illustrating the ineffectiveness associated with consumer-based approach due to carbon leakage and contract re-shuffling when the coverage of programs is incomplete.[2]

To understand the equivalence of market outcomes under policies with different points of regulation, we begin our analysis in Section 2 with a graphical approach to illustrate the impacts of electricity price and 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 graphical approach herein allows for establishing the equivalence of the market outcomes in a simple case, it does not account for some essential features of the electricity market, including the transmission network, the heterogeneity of technologies, and the existence of an independent system operator. Our analysis then develops more detailed models documented in Appendices that account for the aforementioned factors. The detailed model is then applied to the PJM (Pennsylvania-New Jersey-Maryland) Interconnection regional energy market in Section 4. Conclusions are then summarized in Section 5 while the model formulations and proof of equivalence of the consumer- and producer-based regulations is presented in Appendices.

2. Graphical 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; conversely, 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 excise tax, either on the purchases or sales of a good, is imposed on a commodity. Fig. 1 illustrates the impacts of a carbon tax (T^{CO2}) 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^{CO2}, levied by the government. The tax revenue collected by the government is therefore equal to $Q_T \times T^{CO2}$. Compared to the case without the carbon tax T^{CO2}, 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 also offset by the avoided carbon damage. If the avoided carbon damage is exactly equal to the area delineated by B + K, the policy is efficient in this simple case.[3]

Alternatively, producers can be subject to a carbon tax T^{CO2} for their energy production that has CO_2 emissions as a by-product. This is equivalent to shifting the supply curve (S) up by the tax amount of T^{CO2} to the curve S' as shown in Fig. 1. 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 consumer 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 also B + K. This simple graphic-based partial equilibrium analysis illustrates the fact when the market is perfectly competitive, the point-of-regulation, either producers or consumers, will not alter market outcomes. Of course, the situation is much more complicated when endogenous interactions are accounted for in a general equilibrium framework when the prices of input factors of various sectors are also changed.

3. Literature review

Analysis on the incidence of climate change policy is of great interest to economists. For example, using the Consumer Expenditure Survey and an augmented input-output model of the US economy, work by Grainger and Kolstad (2010) shows that a carbon tax on CO_2 emissions is regressive, implying that it has a disproportional impact on the low-income households. Feng et al. (2010) 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 the GHG-based tax would lower marginal abatement costs, and lessen the impacts of low-income households by shifting the burden away from food products. These papers go beyond analyses of a single-sector models, allowing the

[2] Partial coverage can be arised in a situation in which power plants located in different states compete in a regional energy market while they are subject to local regulation by individual state or by a region that has a territory not entirely aligned with that of the regional power market. An example is the PJM (Pennsylvania-Jersey-Maryland) regional electric market and RGGI (Regional Greenhouse Gas Initiative). While there is a significant geographic overlap of two organizations, a number of the PJM states are not part of RGGI, such as New Jersey, Pennsylvania.

[3] In reality, the pre-existence of other taxes, such as an income tax, might interact with the carbon tax or a cap-and-trade program and create further distortion, leading to welfare loss, see for example Goulder et al. (1997).

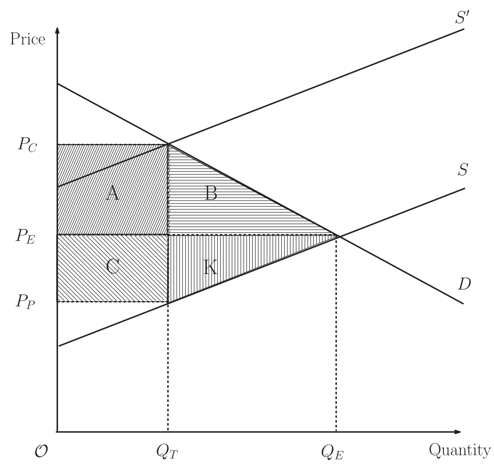

Fig. 1. Impact of carbon tax on market outcomes.

impacts of a tax through supply-demand conditions among different sectors.

Another stream of research focuses only on the energy sector and studies the pass-through of CO_2 permit price to the wholesale power price. Pass-through of the CO_2 permit price depends on a number of factors, e.g., market structure, merit-order changes, and price and demand elasticity. In general, the pass-through is negatively (positively) related to the electricity market demand's (supply's) price responsiveness. If the electricity market demand is not price-responsive, the pass-through is expected to be close to 100%. In contrast, if electricity supply is highly price-responsive, it likely results in a pass-through of close to 0% (Chen et al., 2008).

Using a simulation-based approach, Chen et al. (2008) examine the pass-through and windfall profits in phase 1 of EU ETS (European Union Emission Trading Scheme). 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. A study by Wild et al. (2015), using agent-based modeling, finds an incomplete pass-through for the Australian National Energy Market, especially for the regions with substantial hydro generation. Empirically, with available historical market data, various studies have assessed *ex post* the CO_2 price's pass-through rate. For instance, Sijm et al. (2006) investigate the windfall profit in early stage of EU ETS; Zachmann and Von Hirschhausen (2008) find that rising CO_2 prices of EU ETS permits have a stronger impact on the wholesale electricity prices than falling CO_2 prices (asymmetric effect) in Germany; Fezzi and Bunn (2009) document that a 1% increase in the price of CO_2 permits leads to a 0.32% increase in the electricity prices in the European market; Fabra and Reguant (2014) conclude a nearly 100% pass-through in the Spain power market. More recently, Hinttermann (2016) estimates a pass-through of 84–104% in the German electricity sector. Woo et al. (2017) examine the path-through of the California's C&T (cap-and-trade) program on the wholesale electricity prices of four interconnected market hubs. The study concludes the market is efficiently internalized the CO_2 cost, and producers effectively incorporated CO_2 in their bids into the market as the pass-through is nearly 100%. Finally, a statistically insignificant pass-through also is found by Lo Prete and Norman (2013) 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. Hobbs et al. (2012) analyze a form of "downstream" CO_2 regulation in the electricity sector that requires retail suppliers to buy energy from a mix of sources so as to satisfy an emission standard. The paper finds that the so-called "downstream" regulation neither solves emissions leakage nor leads to a lower procurement cost for consumers, or provides more incentive for energy efficiency than the traditional C&T program. Chen et al. (2011) study the three carbon emission trading programs for the electric power sector considered by the California government under its AB32 (Assemble Bill): a load-based, a source-based, and a first-seller approach. The paper shows that "emission leakage" eliminates most of the emission reductions that the regulations attempt to impose. Further, "contract reshuffling" occurs to such an extent that all the apparent emission reductions resulting from changes in sources of imported power are illusory.

With a growing interest in reducing emissions by regulating consumer behavior through taxation, our contribution to the existing literature is to illustrate that the carbon emissions forensic, specially in energy sector, by explicitly tracking the carbon content of transmission flows in a power grid in order to associate carbon emissions with consumers is *not* necessary since 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 the simple case alluded to in the graphical analysis, we establish the equivalence in market outcomes with consideration of several essential physical and institutional aspects of the electric market, including the transmission network, the grid operator, the heterogeneous technologies, and the ownership of multiple firms. The findings can be generalized to other sectors with a network structure as well as layers of supply chain.

4. Numerical case study

We illustrate the equivalence of the market outcomes under the consumer- and producer-based regulation by solving the model (presented in Appendix A) using PJM regional electric market data. The PJM market serves as a good case study owing to the fact that, within its service territory, the RGGI (Regional Greenhouse Gas Initiative) has been implemented since 2009. We study two main cases, including a consumer-based tax and a producer-based carbon tax. The analysis will limit to the cases of perfectly competitive energy markets as the PJM's State of the Market report indicates that the market is relatively competitive in recent years (PJM, 2018). Additional cases are also considered in order to understand the effect of the tax coverage on the market outcomes when firms are allowed for strategically changing their contracts to avoid carbon tax. We describe the background of the PJM market and RGGI program in Sections 4.1–4.2, the data in Section 4.3, the performance of the baseline in Section 4.4, followed by the numerical results in Sections 4.5–4.6.

4.1. PJM regional power market

Fig. 2 displays the geographic coverage and network of the electricity market simulated in the model, a subset of the current PJM's service territory. 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

[4] The 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 grown 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 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 peak load equal to 143 GW.

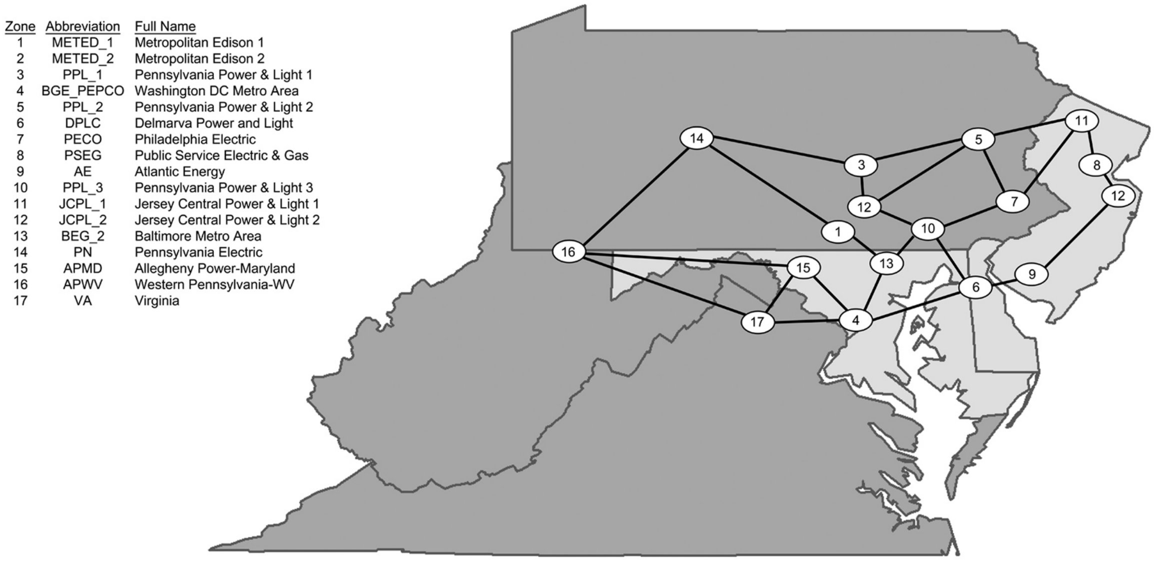

Fig. 2. PJM regional power market transmission network.

one node for better representation of congestion patterns. 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.

4.2. Regional Greenhouse Gas Initiative

Regional Greenhouse Gas Initiative or RGGI is a joint effort initially by ten states in the northeast U.S. targeted at regional CO_2 emissions since 2009 (Regional Greenhouse Gas Initiative, 2018). RGGI's geographic scope has been evolving over time, reflecting changes in political economy, for example. These initial states include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. Light gray color in Fig. 2 represents the sates that were initially affiliated with RGGI in 2009. New Jersey then dropped out of the program in 2011, citing that the permit prices were too low to induce any meaningful emission reduction. The goal of the program is to reduce CO_2 emissions by 10% below 2009's emissions by 2019. The compliance schedule set forth is that the CO_2 emissions will be capped at the 2009's level during 2009–2015, followed by a gradual decline to 10% below the 2009's level by 2019. Fossil-fueled generating units (e.g., gas, oil, and coal) with a capacity greater than or equal to 25 MW fall under the cap. Permits are mainly distributed out by quarterly auctions. Until the recent 2017 third quarter auctions, there are a total of thirty-seven auctions, handing out approximately a total of 885 million short tons of permits.

Table 1
State capacity by fuel type [MW] in study region.

Fuel	MD	NJ	PA	DE	VA	WV	DC
Coal	5127	2139	17,296	804	5742	13,984	0
Gas	2369	11,574	12,673	2467	8498	1211	0
Nuclear	1829	4181	10,015	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	13,265	19,699	46,125	3364	24,695	15,963	755

4.3. Data and assumptions

The main data source for generation characteristics (e.g., capacity, heat rate, emissions rates, fuel costs, etc.) is from SNL Energy with supplementary data obtained from the U.S. Environmental Protection Agency (EPA) eGRID. The capacity is derated based on forced-outage rate to reflect unanticipated plant outages, using data from Generation Availability Data System (GADS) maintained by NERC (North American Reliability Corporation). The states' capacity mix varies considerably. Table 1 summarizes each state's generating capacity by fuel types. The total installed 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 capacity accounts for less than 12% in 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.

The simulation period is year 2012, a leap year that comprises 8784 h.[6] Yearly load is represented by nine periods: permutation of

[5] Further changes were made to model the nodes encompassing more than one state. In particular, we split a node into two (or more) nodes if the initial node contains two (or more) 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 an unlimited transmission capacity. The topology (or network structure) of the additional nodes to the initial system will be radial so the augmented network adds no extra loops. In other words, a new node only interacts with the overall system through its adjacent node. 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 rather polluting state, i.e., Pennsylvania, becomes subjecting to the carbon tax in Section 4.6.

[6] We acknowledge that the simulation year, 2012, is not recent. However, our intention is to illustrate the impacts of a carbon tax with incomplete coverage on market outcomes when it is applied to different entities along the electricity supply chain. We, therefore, believe using 2012's data, even is less desirable, remains valid as we also compare our baseline to the historical data reported by

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 the ozone season. The size of the blocks varies from 455 to 1683 h. Our analysis assumes linear inverse demand function P_{jt} with an elasticity of -0.1.[7] The allowance prices of the CAA (Clean Air Act) Title IV SO_2 and NO_x CAIR programs are assumed to be \$2.5 and \$17/ton, respectively.[8] All the pollutants are measured in short ton, where 1 ton = 2000 lbs. These values are based on 2011 data reported by Energy Information Agency (EIA). Moreover, rather than inferring from existing studies to decide a optimal carbon tax, a carbon tax of \$15/ton is used for our analysis. This level of the carbon tax is sufficiently large to induce utilities or suppliers to change their sales or procurements in order to minimize carbon costs. While this price is significantly higher than the historical market value, i.e., \$3/ton, our interest is not to predict or to duplicate the market prices but to explore the market outcomes under different policy settings.

4.4. Baseline v.s. 2012 data

During 2012, the RGGI CO_2 permit price was reported to bounce around \$2–3/ton (Regional Greenhouse Gas Initiative, 2018). We assume a CO_2 permit price of \$3/ton in our baseline in order to compare the simulation results to historical data reported by PJM and EPA. The purpose of the baseline simulation is to make sure that our results are compatible with the historical data.

For most part, our baseline simulation did a reasonably good job in matching the overall average price of PJM but with a greater dispersion of power prices among nodes. The baseline simulated power price of the entire PJM is \$34.1/MWh, which is slightly higher than historical data of \$33.1/MWh. Overall, our simulation moderately under-estimates the total CO_2 emissions (aggregated over all the states) in the region by a margin of 3% or 7 million tons. Fig. 3 plots the simulated baseline CO_2 emission against the reported historical data in 2012. 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). As seen, the baseline simulation accurately estimates CO_2 emissions from Maryland, New Jersey, and Delaware, but underestimates Pennsylvania's emissions while over-estimating emissions from other states. This is partially because our generating dataset does not include some power plants located in western Pennsylvania.[9]

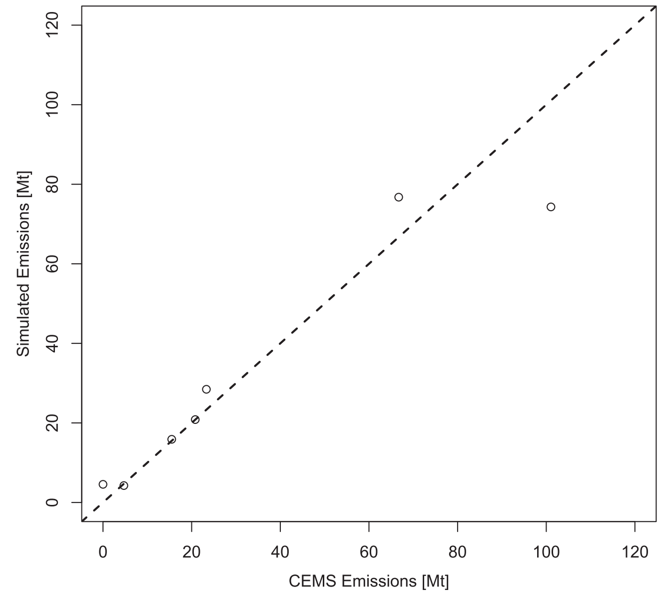

Fig. 3. Plot of simulated emissions of Baseline Case (carbon tax (permit) = \$3/ton) against Continuous Emission Monitoring Systems (CEMS) reported emissions in 2012 (Air Emission Measurement Center, 2018).

However, we are less concerned about the results of the comparison 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 the *qualitative* difference when comparing the results under different cases.

4.5. Main results

Table 2 presents the main results of the analysis when the coverage is complete. The table contains three parts. The upper part gives prices, total sales, regulated CO_2, and total emissions. The row "regulated CO_2" represents the amount of emissions that is priced by the carbon tax. The middle part displays the social surplus outcomes. The lower part further breaks the CO_2 emissions by each state. The three columns (1)–(3) correspond to cases of the consumer-based, the producer-based regulation, and the baseline case, respectively.

Consistent with the conclusions in Section 2 and Appendix B, policies with different points 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 these two cases. The producer surplus, the ISO's revenue (congestion rent), and the government tax, which is calculated as the tax rate (15\$/t) multiplied with the total regulated emissions, are equivalent between the two cases. Since the consumer-based regulation is formulated as a

(footnote continued)
Continuous Emission Monitoring Systems (CEMS) (Air Emission Measurement Center, 2018). Moreover, our analysis based on the latest released data by EPA's Emissions & Generation Resource Integrated Database (eGRID) of 2016 eGRID (2018) and 2012 eGRID (2014) indicates that, relatively, CO_2 emission rate among states does not change significantly. For instance, the output CO_2 emission rate in ascending order in 2012 is NJ (0.24), VA (0.40), PA (0.52), MD (0.60), DC (0.62), DE (0.63), and WV (1.00), compared to NJ (0.28), VA (0.41), PA (0.43), DE (0.52), MD (0.53), DC (0.78), and WV (1.01), where the values in the parentheses are emission rate [tons/MWh]. In order words, in contrast to 2012, NJ, VA, and PA remain relatively less polluting while WV is still mostly polluting state in 2016. We thus believe that the qualitative aspects of our finding will remain valid had 2016 (latest) data were used.

[7] The linear inverse demand function for each period is obtained by solving a cost-minimization problem, one for each location and period, that satisfies the fixed demand q^*_{jt} reported by PJM. Together with the dual variables (p^*_{jt}) of demand constraints as well as the assumed demand elasticity, we then construct linear demand functions, one for each node j and period t, that pass through (p^*_{jt}, q^*_{jt}).

[8] The price of both the SO_2 (Sulfur Dioxide) trading program under the CAA IV as well as EPA's Clean Air Interstate Rule (CAIR) program of the NO_x (Nitrogen Oxides) permits has declined drastically since 2007. For example, SO_2 stood at \$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 in response to the uncertainty of the program as the District of Columbia Court of Appeals ruled in favor of the State of North Carolina by striking down CAIR in July 2008. Even when the court reinstated the program temporarily the following December until the EPA could finalize a replacement plan, with certain restrictions were put on the implementation, the market essentially collapsed.

[9] The 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.

Table 2
Results of the consumer- and producer-based regulation under complete coverage.

Point of regulation	Consumers (1)	Producers (2)	Baseline (3)
Carbon tax [$/ton]	15.0	15.0	3.0
Sale-weighted Price [$/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$]	7471.9	7471.9	4398.4
Consumer/Utility Surplus [M$]	324,780.0	324,780.0	330,372.2
ISO Revenue [M$]	849.9	849.9	978.1
Social Surplus [M$]	333,101.8	333,101.8	335,748.8
Government [M$]	3277.0	3277.0	89.12
CO_2 [10^6 tons]			
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
DC[a,b]	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).

"joint" optimization problem faced by the utilities and the consumers in Appendix A, the consumers surplus in this case is represented by the surplus earned by the utilities, which is equal to the consumers surplus in the producer-based scenario. Compared to the baseline, a complete coverage of producer-based and consumer-based regulation with a higher carbon tax ($15/ton) directly deter power outputs from more high-polluting sources, especially power plants located in Pennsylvania from 157.9×10^6 MWh to 151.3×10^6 MWh (not shown). 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 consumption by 5×10^6 MWh.

When a carbon tax is applied only to a subset of states within an inter-connected regional power market, the equivalence between the consumer-based and the producer-based regulation will not likely hold even if using more recent data. This is mainly because only the sales destinated to a node, subject to the policy, incur the carbon costs while other sales are exempted from the carbon tax. For simplicity, suppose consumers or producers at node A must pay a CO_2 tax while node B is not subject to any CO_2 tax. The equivalence between that a CO_2 tax applies to consumers in node A versus to producers in node A that we observed in Table 2 is unlikely to hold because power trading between nodes A and B. For our analysis, we assume only those nodes associated with states that are part of the current RGGI will be subject to the carbon tax in order to examine the impact of consumer-based and producer-based regulation 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 the reset of the nodes are exempted from the carbon tax.

Tables 3–4 report the outcomes under the partial or incomplete coverage. Table 3 gives the market-related variables, and Table 4 displays the state-specific power price and CO_2 emissions. A number of observations emerge from the tables. First, in comparison to the producer-based regulation (right) the sale-weighted price is lower by $4/MWh while the total CO_2 emissions are higher under the consumer-based regulation by 5.2×10^6 tons. This is mainly because under the

Table 3
Economic rents and market variables 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/Utility Surplus [M$]	334,000.4	328,828.6
ISO Revenue [M$]	906.7	1444.2
Social Surplus [M$]	336,431.9	332,989.1
Government [M$]	0	222.8

Table 4
State-level CO_2 emissions under the partial coverage.

State\Regulation	CO_2 emissions [10^6 tons]		Power price [$/MWh]	
	Consumers (1)	Producers (2)	Consumers (1)	Producers (2)
Maryland[a]	27.91	11.63	29.58	37.15
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.

consumer-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 in the regulated states is allowed to procure or to swap their contracts so that the imports become less polluting in order to avoiding the carbon tax. In our simulation, without any existing forward contracts, utilities within the regulated states can avoid the carbon tax entirely by importing zero-emitting power so that "regulated CO_2" becomes zero, see also discussions in Woo et al. (2017). 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 CO_2 is roughly 14.9×10^6 tons (summation of emissions over Maryland, Delaware and Washington, DC) while the total surrendered tax is equal to $222.8 M under the producer-based regulation. Second, the higher power prices experienced in the producer-based regulation means a higher producer surplus by $514 M or 15% even the producers in the regulated states are required to pay for the carbon tax. Third, the lower power price under the consumer-based regulation benefits the consumers (jointly with the utility) by $5171 M or roughly by 1.5%. Finally, when considering carbon tax revenues, the social surplus under the consumer-based regulation is better off as it is less stringent by design.[10]

Turning our attention to the power prices and the state-level emissions, producers within the regulated region when subjected to the

[10] Of course, we are fully aware that the damage caused by additional CO_2 emissions (5.2×10^6 tons) should be properly accounted for when comparing social surplus under the carbon tax regulation. Our analysis then focuses the extent that CO_2 emissions can be effectively priced under each policy. We also exclude government's tax revenue form social surplus since government does not directly participate in the market, similar to fuel costs that have to be paid by producers to generate power.

producer-based regulation will incorporate the carbon tax in their marginal cost (compared to the consumer-based regulation), thereby leading to an increase in the power price. Higher power prices in the regulated regions incite the power plants located in unregulated regions to increase their exports, also leading to higher power prices locally. Therefore, the state-level power prices under the producer-based regulation raise by 3–25% compared to their counterparts under the consumer-based policy. In comparison to the consumer-based regulation, the CO_2 emissions from regulated states under the producer-based regulation decline by a total of 22.0×10^6 tons. This decline is then offset by an increase in the CO_2 emissions by 16.8×10^6 tons from unregulated states, leading to an overall net decrease of 5.2×10^6 tons. Overall, the CO_2 emissions tend to be amassed in unregulated states under the producer-based regulation compared to the consumer-based regulation as the latter regulation allows for contract re-arrangements.

4.6. Sensitivity analysis

As seen in Section 4.5, the equivalence between the consumer- and producer-based regulation no long holds when the coverage of the regulation is incomplete. In particular, the Section 4.5 suggests that the sector can avoid the carbon tax entirely by procuring power from zero-emitting energy sources. This section reports two sets of sensitivity analysis.

4.6.1. Greater coverage

To see if the procuring zero-emitting energy sources is less likely an effective strategy when the program is expanded to a greater geographic scope, especially those states with higher energy demand. We perform a sensitivity analysis by including Pennsylvania to the RGGI program by designating additionally ME2, PE, PPL1, PPL2, PPL3, PE, PS (partial), WV (partial), and PN to also be subject to the carbon tax.

Tables 5–6 report 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 becomes more effective in regulating emissions. More specifically, the power sector cannot avoid the consumer-based regulation entirely by importing zero-emitting power to the regulated regions, thereby a generalizable result if more recent data were used. A \$15/ton carbon tax is capable of regulating 17.6×10^6 tons of emissions under the consumer-based regulation, which is less than 25% of that under the producer-based regulation, 71.1×10^6 tons. That is, more than 75% of carbon emissions are “unpriced” under the consumer-based regulation. The broader extent of the carbon tax under the producer-based regulation effectively elevates the power prices, leading to a less amount of power sales. The social surplus under the producer-based regulation, excluding the benefit of 5 million tons of avoided carbon emissions, is still lower than that of the consumer-based regulation.

Table 6 suggests that except for Delaware with an increase of CO_2 emissions by 4.7×10^6 tons, other regulated states (Maryland, Pennsylvania, and Washington, 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 5
Economic rents and market variables 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	71.1
Total Sales [10^6 MWh]	433.6	431.2
Producer Surplus [M\$]	3232.8	6125.4
Consumer/Utility Surplus [M\$]	332,134.4	326,228.3
ISO Revenue [M\$]	791.9	605.1
Social Surplus [M\$]	336,159.2	332.958.8
Government [M\$]	264.6	1065.6

Table 6
State-level CO_2 emissions under the partial coverage with Pennsylvania.

State\Regulation	CO_2 Emissions [10^6 tons] Consumers (1)	Producers (2)	Power Price [\$/MWh] Consumers (1)	Producers (2)
Maryland[a]	27.91	18.46	39.14	41.68
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.

Table 7
Economic rents and market variables under the targeted coverage.

Variables\Regulation	Consumers[a] (1)	Producers[a] (2)	Consumers[b] (3)	Producers[b] (4)
Sale-weighted Price [\$/MWh]	40.09	42.56	33.90	43.22
Total CO_2 [10^6 tons]	224.47	222.47	226.26	226.17
Regulated CO_2 [10^6 tons]	73.62	62.32	0.18	94.61
Total Sales [10^6 MWh]	432.8	431.98	434.67	431.25
Producer Surplus [M\$]	4505.8	4142.3	1680.2	5854.1
Consumer/Utility Surplus [M\$]	330,030.7	326,698.1	330,452.9	326,430.3
ISO Revenue [M\$]	778.5	2130.6	904.1	539.4
Social Surplus [M\$]	335,315.0	332,950.0	336,428.5	332,823.7

[a] Coverage includes Maryland, New Jersey, Delaware, Virginia, and Washington DC.
[b] Coverage includes West Virginia and Pennsylvania.

4.6.2. Targeted coverage

The second set of the sensitivity analysis compares two cases, differed by which states to be regulated. The results are summarized in Table 7. This is motivated by the fact that policymakers might decide to tailor a consumer-based policy to regulating importing states, column (1), or a producer-based policy to regulating exporting states, column (4) in order maximize policy effectiveness. Columns (1)–(2) and (3)–(4) respectively represent the cases in which a policymaker regulates importing states (including Maryland, New Jersey, Delaware, Virginia, and Washington DC) and exporting states (including West Virginia and Pennsylvania). In general, cases with consumer-based regulation lead to a higher social surplus with greater CO_2 emissions. When regulating the importing states, columns (1)–(2), consumer-based regulation actually can price more CO_2 than its producer-based regulation counterpart, 73.62 v.s. 62.32 tons. However, overall emissions in column (1) remain to be greater than that of column (2) due to emission leakage. In other words, regulating importing states under the consumer-based policy could effectively increase the amount of priced CO_2 emissions, a result that could be qualitatively generalized. Regulating consumers in exporting states, column (3), is only marginally effective compared to no regulation as the regulated CO_2 is close to zero while its counterpart in column (4) can regulate more than 40% of total CO_2 emissions in the system.

5. Conclusion and policy implications

Climate policy has mostly focused on regulating production side of the energy sector. There is 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 that has received some attention recently is to develop ways to track power flows in a transmission network in order to associate carbon content with the end-users' power consumption. We refer this action in this paper as "carbon forensic." Reliable and accurate flow tracking would lay out the foundation by which a carbon tax can be applied to regulating carbon emissions from demand side.

Economic theory suggests that a value-added or a excise tax on consumers would produce the same market equilibrium compared to the case when the same tax, instead, is imposed on producers. This paper develops market equilibrium models, one for consumer-based regulation and one for producer-based regulation, to study these two approaches 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. The paper concludes that this equivalence principle, which is well-known in microeconomics, transcends to a power market when the heterogeneous technologies, the physical network, and other more realistic considerations are accounted for. That is, even with more realistic considerations of the power sector, the equivalence principle based on economic theory alluded in Section 2 remains correct. However, such equivalence is valid only if the carbon tax is applied to all generators in the power market, namely complete coverage.

With an incomplete coverage, under the consumer-based regulation, only the power sales to regulated regions will be subject to a carbon tax while the sales to other unregulated regions will be exempted from the carbon tax. On the contrary, the producer-based regulation regulates only the producers from the regulated regions. The incomplete coverage provides the power market with economic incentives for a reliance on power imports (thereby exempted 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 less ineffectively regulating pollution when comparing to the complete coverage case.

The analysis numerically compares the performance of consumer-based and producer-based regulation 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 results in higher overall emissions. On the other hand, the broader extent of regulation under the producer-based regulation (in contrast to the consumer-based regulation) elevates power prices, thereby encouraging emission leakage from unregulated regions. When the program is relatively less complete, the carbon tax can be entirely avoided by consumers through utilizing contract reshuffling or relying on imports with zero-emitting energy to satisfy their energy demand under the consumer-based regulation (Table 3). 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 tax coverage under the producer-based regulation diminishes the ability of the sector to avoid regulation entirely through contract rearrangements or so-called laundering as discussed in Woo et al. (2017). Overall, the effectiveness of regulation in the consumer-based regulation, measured by the amount of CO_2 emissions that are priced under the tax, remains lower in comparison to the producer-based regulation, except under the targeted-coverage cases. The social surplus comparison is less straightforward in this case owing to the fact that the damage cost by the additional CO_2 is not accounted for.

Our analysis is subject to a number of limitations. First, our analysis of the consumer-based approach is limited to the case at which power produced from regulated regions is not subject to any regulation when it is exported to other unregulated regions. In reality, policies, such as California's AB32 in US, also requires in-state generation to be subject to carbon regulation even if it is sold to other unregulated regions. Second, we ignore the existence of forward contracts in our analysis. Since forward contracts typically account for more than 80% of power sales, the existence of forward contracts might diminish the ability of producers or 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.

Policy choices have profound and long-lasting impact on the regulated industry affecting economic rent distribution among suppliers, consumers, the grid operator and the 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. It could further require a regulatory reform to revise tariff structures, resulting in daunting transaction costs. When the program's coverage is complete, our conclusion is that a producer-based regulation is more efficient because 1) the existing system (at least in the US context), such as USEPA's Continuous Emission Monitoring Systems, is already in place, and 2) the market outcomes are equal to the consumer-based approach. Moreover, if the tax program is incomplete, neither of the approaches is efficient, owing to contract reshuffling, leading to so-called emission leakage. The magnitude of the carbon to be taxed under the consumer-based regulation is expected to be smaller. Even with a more sophisticated hybrid approach designed to avoid emission leakage, such as first-delivery regulation with a default rate under California AB32 in US, the efficiency of the program remains questionable as shown by Bushnell et al. (2014). To efficiently regulate 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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Appendix

We present detailed models in this section. The appendix begins by the problem faced by the grid operator and consumers in (Appendix A.1), which is commonly shared by both producer- and consumer-based regulation models. Models of the producers and utility or load-serving entities under the producer- and consumer-based regulation are presented in Appendices A.1 and A.2, respectively. Together with the market-clearing conditions, the resulting first-order conditions from the problem faced by the consumers, the producers, and the grid operator constitute a complementarity problem, which defines the equilibrium of the market. Proof of the equivalence between the producer-based and consumer-based regulation is presented in Appendix B.

Appendix A

A.1. Grid operator and consumers

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

$$\begin{aligned}&\underset{y_{it}}{\text{maximize}} \quad \textstyle\sum_{i,t} w_{it}y_{it}\\ &\text{subject to} \quad -T_k \le \textstyle\sum_i PTDF_{ki}y_{it} \le T_k,\ (\lambda_{kt}^-,\ \lambda_{kt}^+)\ \forall\ k,\ t,\end{aligned} \tag{A1}$$

where y_{it} is the amount of power delivered from the hub to node i in time t 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.) w_{it} is the transmission charge to bring power from the hub to j, dual variables of the market-clearing condition in (A10). 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. (1988).[11] 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 first-order conditions for the grid operator's problem (A1) are defined as follows:

$$0 \le \lambda_{kt}^+ \perp \sum_i PTDF_{ki}y_{it} - T_k \le 0 \tag{A2}$$

$$0 \le \lambda_{kt}^- \perp -\sum_i PTDF_{ki}y_{it} - T_k \le 0 \tag{A3}$$

$$w_{it} + \sum_k PTDF_{ki}(\lambda_{kt}^- - \lambda_{kt}^+) = 0. \tag{A4}$$

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

$$p_{jt}^E = P_{jt}(Q_{jt}),\ \ \forall\ j,\ t. \tag{A5}$$

Nodal consumption is equal to $Q_{jt} = \sum_{f,i,h\in H_{if}} x_{fihjt}$, where x_{fihjt} is the quantities sold from i to node j from the power plant h owned by producer f with $P'_{jt} \le 0$ and $P''_{jt} \le 0$. The notation H_{if} defines the set of power plants owned by firm f in region/node i.[12]

A.2. Producer-based regulation

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 (A6) by determining output level x_{fihjt} of plant h located at node i that sell to node j:[13]

$$\underset{x_{fihjt}}{\text{Maximize}} \sum_{i,h\in H_{if},j,t}\left(p_{jt}^E - w_{jt} + w_{it}\right)x_{fihjt} - \sum_{i,h\in H_{if},t} C_{fih}\left(\sum_j x_{fihjt}\right) - \sum_{i,h\in H_{fi},j,t} T^{CO2}E_{fih}x_{fihjt} \tag{A6}$$

$$\text{subject to} \sum_j x_{fihjt} \le X_{fih},\ (\rho_{fiht})\ \forall\ i,\ h\in H_{if},\ t, \tag{A7}$$

$$x_{fiht} \ge 0,\ \forall\ f,\ i,\ h \in H_{if},\ t.$$

The term $p_{jt}^E - w_{jt} + w_{it}$ in the objective function is the per MWh revenue, in which producer f sells x_{fihjt} of power produced by plant h in node i to consumers at node j and earns p_{jt}^E, while paying the transmission charge $-w_{jt} + w_{it}$ to the grid operator to bring power produced in i to consumers in j. The term w_{it} accounts the service by the generator fih to provide "counterflow" to offset or relieve the congestion in the direction from the hub to node i. (The implicitly assumption is that power sales from i to j is routed through the hub.) Thus, the transmission charge to bring power from i to j is equal to $w_{it} - w_{jt}$. The terms $C_{fih}(\sum_j x_{fihjt})$ and $\sum_{i,h\in H_{fi},t} T^{CO2}E_{fih}x_{fihjt}$ are, respectively, the total cost of production and CO_2 emission cost, where T^{CO2} and E_{fih} denote the carbon tax and the emission rate, respectively. We assume that $C'_{fih} > 0$ and $C''_{fih} \ge 0$.

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 generation capacity X_{fih}.

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

$$0 \le x_{fihjt} \perp \left(p_{jt}^E - w_{jt} + w_{it}\right) - C'_{fih} - T^{CO2}E_{fih} - \rho_{fiht} \le 0,\ \forall\ f,\ i,\ h\in H_{if},\ j,\ t \tag{A8}$$

[11] This approach is also based on the Kirchoff laws. The PDTF is a matrix with a dimension of $K \times I$, where K and I are number of transmission lines (also referred to as flowgates) and regions in a network, respectively. For an injection from the hub to a region/node i in period t, y_{it}, the term $PTDF_{ki}y_{it}$ represents the flow in the transmission line k as a result of y_{it}. If there are more than one injection-withdrawal, the overall flow in the transmission line k can be calculated by $\sum_i PTDF_{ki}y_{it}$. (This is also known as the superposition principle.) A similar approach has also been used to model the electric flow in a power market, see, for example, Egerer et al. (2016); Kunz et al. (2017); Perez et al. (2016); Mount et al. (2012), and Bertsch et al. (2017).

[12] We use the set i and j inter-exchangeably through out the paper to ease the presentation.

[13] The model is generalized to allows demand and supply in all i or j region.

$$0 \le \rho_{fiht} \perp \sum_j x_{fihjt} - X_{fih} \le 0, \forall f, i, h \in H_{if}, t. \tag{A9}$$

Condition (A8) states that if the revenue minus transmission fee ($p^E_{jt} - w_{jt} + w_{it}$) is less than the sum of marginal production cost (C'), carbon cost ($T^{CO2}E_{fih}$), and capacity scarce rent (ρ_{fiht}), the sales (x_{fihjt}) equal zero.

Market Clearing Conditions One condition is essential to calculating the market equilibrium. The condition is associated with power transmission to ensuring balance of the physical system, with the transmission charge or wheeling fee, w_{it}, implicitly defined. This condition states that total sales from i to other nodes, $\sum_{f,h\in H_{if},j} x_{fihjt}$, minus the total sales from other nodes to i, $\sum_{f,h\in H_{jf},j} x_{fjhit}$, equals to y_{it}.

$$w_{it}\text{: free} \quad \sum_{f,h\in H_{if},j} x_{fihjt} - \sum_{f,h\in H_{jf},j} x_{fjhit} = y_{jt}, \forall i, t, \tag{A10}$$

The set of conditions (A2)–(A5), and (A8)–(A10) defines the market equilibrium of the producer-based regulation.[14]

A.3. Consumer-based regulation

Consumers/Utility We assume that a utility or load-serving entity in region j, who procures the electricity on behalf of consumers through bilateral contracts with producers, will be the entity in compliance with the regulation.[15] We, therefore, model the problem faced by the consumers and the utility jointly as follows:

$$\underset{z_{fjhit}}{\text{Maximize}} \sum_t \int_0^{d_{it}} p^E_{it}(q)\mathrm{d}q - \sum_{j,f,t} (p_{fjhit} + T^{CO2}E_{fjh})z_{fjhit} \tag{A11}$$

subject to$z_{fjhit} \ge 0, \forall j, h \in H_{jf}, t.$

A utility decides the amount of power, z_{fjhit}, to procure from power plant h at j node owned by firm f through a bilateral contract while subjecting to a carbon tax. Its total sales are d_{it}, which are equal to $\sum_{f,j,h\in H_{jf}} z_{fjhit}$. The term p_{fjhit} 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^E_{it}, will be equal to the settlement price p_{fjhit} plus the emission cost $T^{CO2}E_{fjh}$.

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

$$0 \le z_{fjhit} \perp p^E_{it} - p_{fjhit} - T^{CO2}E_{fjh} \le 0 \tag{A12}$$

This condition indicates that if the marginal benefit (p^E_{it}) is less than the sum of price paid to producers (p_{fjhit}) and carbon cost ($T^{CO2}E_{fjh}$), the procured quantity (z_{fjhit}) is equal to zero.

Producers Under the consumer-based regulation, the producer's problem needs to be modified by eliminating T^{CO2} term from the objective function (A6). This yields the revised problem as follows:

$$\underset{x_{fihjt}}{\text{Maximize}} \sum_{i,h\in H_{fi},j,t} (p_{fihjt} - w_{jt} + w_{it})x_{fihjt} - \sum_{i,h\in H_{fi},t} \left(C_{fih}\left(\sum_j x_{fihjt} \right) \right) \tag{A13}$$

$$\text{subject to} \sum_j x_{fihjt} \le X_{fih}, (\rho_{fiht}) \ \forall i, h \in H_{if}, i, t, \tag{A14}$$

$x_{fihjt} \ge 0, \forall i, h \in H_{if}, j, t.$

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

$$0 \le x_{fihjt} \perp (p_{fihjt} - w_{jt} + w_{it}) - C'_{fih} - \rho_{fiht} \le 0, \forall f, i, h \in H_{if}, j, t \tag{A15}$$

$$0 \le \rho_{fiht} \perp \sum_j x_{fihjt} - X_{fih} \le 0, \forall f, i, h \in H_{if}, t. \tag{A16}$$

, which (A16) is equivalent to (A9).

Market-Clearing Conditions In addition to (A10), one more condition is necessary to calculating a market equilibrium. The condition equates the offer (z_{fihjt}) and the purchase (x_{fihjt}) quantifies in the bilateral transactions with the settlement prices, p_{fihjt} implicitly defined by Eq. (A17).

$$p_{fihjt}\text{: free} \quad x_{fihjt} = z_{fihjt}, \forall i, f, h \in H_{if}, j, t. \tag{A17}$$

The collection of conditions (A2)–(A5), (A10), (A12) and (A15)–(A17) define the market equilibrium under the consumer-based regulation.

Appendix B. Equivalence of consumer- and producer-based regulation

As alluded to in Section 2, the two regulations differing in their point of regulation, one by producers in Appendix A.2 and one by consumers in Appendix A.3, are equivalent in theory. A comparison of the two sets of equilibrium conditions suggests that they differ by (A8) of producer-based regulation, and (A15) and (A17) of consumer-based regulation. To establish the equivalence, we assume that $x_{fihjt} = z_{fihjt} > 0$ in (A17) for all

[14] The theoretical properties of the resulting complementarity problem, including existence and uniqueness of the solutions, can be found in Hobbs (2001) and Cottle et al. (1992). 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.

[15] A similar formulation is used previously to model California AB32 (Chen et al., 2011).

$i, f, h \in H_{if}, j, t$. Eq. (A12) implies that

$$p_{fihjt} = p_{jt}^{E} - T^{CO2}E_{fih}. \tag{B1}$$

In other words, the bilateral settlement price paid by utility to producers, p_{fihjt}, equals the price paid by consumers, p_{jt}^{E}, minus the CO_2 tax or $T^{CO2}E_{fih}$. Had a producer owned a zero-emitting power plant, it will be fully compensated by the price paid by consumers. Otherwise, it will surrender an emission tax of $T^{CO2}E_{fih}$ to government. Given (B1), we can then substitute the term p_{fihjt} with $p_{jt}^{E} - T^{CO2}E_{fih}$, Eq. (A15) becomes

$$0 \le x_{fihjt} \perp \left(p_{jt}^{E} - w_{jt} + w_{it}\right) - C'_{fih} - T^{CO2}E_{fih} - \rho_{fiht} \le 0, \forall f, i, h \in H_{if}, j, t \tag{B2}$$

, which is equivalent to Eq (A8) in the producer-based regulation. This establishes equivalence of the two regulations differing in their points of regulation, i.e., consumers and producers.[16]

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[16] In cases when m of x_{fihjt} (or z_{fihjt}) equal zero, one can assign zeros to those m variables, and the same approach can be applied to show the equivalence of the solutions of remaining N-m conditions, where N is the total (complementarity) conditions in the problem.