How Market Power Can Suppress the Effect of Carbon Policies in Wholesale Electricity Markets

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Abstract

Market power and unpriced carbon externalities are two failures that are common to wholesale electricity markets. We use a case study that is based on Japan's wholesale electricity market to examine the impacts of addressing the former. Specifically, we compare Pigouvian taxes on carbon emissions and a renewable portfolio standard, which is an alternative indirect policy measure that is used commonly to reduce carbon emissions. We find that the benefits of Pigouvian taxes in reducing carbon emissions can be suppressed if market power is not addressed. This effect depends upon market structure, though. For the case of Japan's electricity sector, this effect of market power is due to the industry being highly asymmetric. Carbon pricing increases the cost of carbon-intensive electricity-generation technologies. Lower-carbon generation technologies are held by firms with market power, which have incentives to withhold their capacity from the market to increase wholesale prices and their profits. As such, carbon pricing can result in high prices but muted carbon-emissions reductions. These impacts of carbon pricing are not observed if the wholesale electricity market is perfectly competitive.

Keywords: Electricity market, energy policy, climate-change policy, carbon price, market power

1. Introduction

Market failure is a challenge in designing wholesale electricity markets [1]. Among these failures are the exercise of market power [2–5] and unpriced externalities, *e.g.*, of carbon emissions [6, 7].

Some jurisdictions are proposing price- or tax-based policies to internalize the cost of carbon. Among these jurisdictions is Japan, which has proposals for carbon pricing across its economy [8]. Japanese industry tends to oppose carbon pricing, a common refrain being that carbon pricing harms or strands investments, increases energy prices, reduces Japanese industry's competitiveness, and yields limited carbon reduction (due to leakage).[1] These criticisms are made despite surveys and empirical analysis showing that carbon pricing can reduce carbon emissions, mitigate leakage, and avoid negative economic impacts [9]. Despite industry opposition, public acceptance and approval of carbon pricing could be increased through dividend payments and proper education of and communication with affected stakeholders [8–10]. Asakawa *et al.* [10] review and discuss the political process that could be employed to introduce carbon pricing in Japan.

Many works that examine carbon pricing assume a perfectly competitive market or neglect the potential exercise of market power [7, 11]. This assumption leads to the use of production-cost or cost-based optimization models. As such, most of these analyses suggest unequivocally that carbon pricing is an efficient policy mechanism for addressing climate change. As an example of carbon-policy analysis that considers market power, Newbery [12] examines European Emissions Trading Scheme, which fixes the allowed quantity of carbon that can be emitted from covered sectors of the economy. Newbery finds that the scheme could exacerbate the market power of natural-gas suppliers. As another example, Downward [13] studies the combined impacts of market power, unpriced carbon externalities, and transmission congestion in wholesale electricity markets. Downward demonstrates that using a carbon price to internalize the unpriced externality can increase carbon emissions, through the combined effects of market power and transmission congestion. Thus, Downward demonstrates that addressing one market failure (but not others) can yield a greater efficiency loss than leaving all market failures unaddressed.

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[1] https://www.keidanren.or.jp/policy/2022/079_honbun.pdf

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In this paper, we apply supply-function equilibrium (SFE) [14] to explore the interplay between carbon policy and market power. SFE is a game-theoretic model [15, 16] that captures strategic profit-maximizing behavior by suppliers. A chief strength of SFE is that it assumes a strategic variable that reflects the actual operation of most wholesale electricity markets. Unlike Bertrand or Nash-Cournot models [17], which assume that firms compete in prices or quantities, respectively, SFE assumes that each firm commits to a supply function, which specifies the minimum price at which it will supply different quantities. Most spot wholesale electricity markets operate in such a fashion, whereby suppliers submit discrete supply functions that consist of multiple price/quantity pairs. SFE is validated empirically [18, 19], by comparing computed equilibria to historical market data. Given these strengths of the model, SFE is used in the literature to study different aspects of the design, operation, and efficiency of wholesale electricity markets [20–26].

We apply our SFE model to a case study that is based on Japan's electricity industry to conduct carbon-policy analysis in the presence of market power. We show that carbon pricing can have muted carbon-reduction impacts. This result stems from the asymmetric nature of Japan's electricity industry, whereby natural-gas-fired generation is owned by firms with outsize market power. Such firms exercise market power by withdrawing their generating capacity from the market. With carbon pricing, this behavior causes increased dispatch of carbon-intensive coal-fired generation in the presence of market power as compared to a perfectly competitive benchmark. As such, prices and firms' profits increase and carbon-emission reductions decrease in the presence of market power as compared to with perfect competition. Altogether, our work demonstrates that carbon and other environmental and energy policies should consider the underlying structure of the markets in which they are applied.

The remainder of this paper is structured as follows. Section 2 outlines our SFE model. Section 3 summarizes our case-study data and implementation. Appendix A provides further technical details of how we compute SFE. Section 4 provides case-study results. Section 5 concludes and discusses policy implications of our work.

2. Supply-Function Equilibrium Model

2.1. Preliminaries

We assume that the market consists of a set, $\mathcal{I}$, of strategic profit-maximizing firms. For all $i \in \mathcal{I}$, firm i has a cost of supply that is given by, $c_i(q)$, where q is given in MW, and a Q_i-MW supply capacity. The cost functions are time-invariant, at least twice continuously differentiable, and we assume that $c'_i(0) = c'_j(0)$, $\forall i, j \in \mathcal{I}$.

We let D denote demand, which is given in MW. For all $i \in \mathcal{I}$, firm i is assumed to commit to a supply function, $q_i(p)$, which specifies firm i's MW of supply as a function of the energy price, p. We assume that $\forall i \in \mathcal{I}$, $q_i(p)$ is at least twice piecewise continuously differentiable. We assume that the market has a price cap, which we denote as $\bar{p}$. Appendix A details the impact of $\bar{p}$ on equilibrium calculation.

2.2. Supply-Function Equilibrium Derivation

SFE finds each firm's best supply function, in the sense that $\forall i \in \mathcal{I}$, $q_i(p)$ maximizes firm i's profit, while holding the supply functions of its rival firms fixed. A set of supply functions that satisfies this condition constitutes a Nash equilibrium [15]. To compute such an equilibrium, we begin by expressing, $\forall i \in \mathcal{I}$, firm i's profit as:

$$\max_p \pi_i(p) = p \cdot q_i(p) - c_i(q_i(p)).$$

which can be expressed equivalently as:

$$\max_p \pi_i(p) = p \cdot \left[D - \sum_{j \in \mathcal{I}, j \neq i} q_j(p) \right] - c_i \left(D - \sum_{j \in \mathcal{I}, j \neq i} q_j(p) \right), \quad (1)$$

using the market-clearing condition that:

$$\sum_{j \in \mathcal{I}} q_j(p) = D, \quad (2)$$

at the market-clearing price. The first-order necessary condition [27] for an optimum of (1) is:[2]

$$D - \sum_{j \in \mathcal{I}, j \neq i} q_j(p) = \left[p - c'_i \left(D - \sum_{j \in \mathcal{I}, j \neq i} q_j(p) \right) \right] \cdot \sum_{j \in \mathcal{I}, j \neq i} q'_j(p). \quad (3)$$

Substituting (2) into (3) yields:

$$q_i(p) = [p - c'_i(q_i(p))] \cdot \sum_{j \in \mathcal{I}, j \neq i} q'_j(p), \quad (4)$$

which is a set of coupled ordinary differential equations (one $\forall i \in \mathcal{I}$) that characterizes an SFE. Thus, computing an SFE amounts to finding a set of supply functions that satisfies (4) simultaneously $\forall i \in \mathcal{I}$ [14].

3. Case-Study Data and Implementation

We apply our model to a case study that is based on Japan's wholesale electricity market, using fiscal-year 2017

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[2] We neglect second-order sufficient conditions because they do not help with SFE computation [14].

(FY2017) historical data. Japan is an electrical (and physical) island, so we model its electricity market in isolation of neighboring countries and do not account for electricity imports or exports [28]. Japan's electricity industry is undergoing restructuring that dates back to 2005 [29]. As part of these efforts, the generation and retail businesses of electric utilities are separated from the ownership and operation of transmission and distribution infrastructure [30]. Since 2005, the volume of electricity that is traded on the centralized spot market is growing.

We use a four-step process to determine demand, the set, $\mathcal{I}$, of strategic firms, and the generating capacities and cost functions of firms from publicly available data.[3] First, historical hourly FY2017 generation data for each utility are aggregated to determine total hourly load.

Second, we divide the generating fleet into two sets. The first set is fossil-fueled technologies, which consist of coal-, natural-gas-, and oil-fired units. The second set is all of the remaining technologies. We assume that fossil-fueled technologies are dispatchable, in the sense that the firms that operate such units can adjust their output based on market conditions (*e.g.*, prices). We assume that the second set of technologies is non-dispatchable and that they operate based on historical FY2017 data. This is a reasonable assumption, because these technologies have rigid physical, regulatory, or other constraints that govern their operation. Thus, we subtract the fixed historical hourly output of the non-dispatchable generators from historical hourly load to obtain residual load that must be served using the dispatchable generators. We focus our modeling and SFE computation on the dispatchable-generator fleet.

The third step of our process is to compute the inverse of Herfindahl-Hirschman Index (HHI) of the dispatchable technologies. The inverse of HHI, which is about eight for our case study, can be used to estimate the number of strategic firms [31]. Given the value of the inverse of HHI, we assume that the eight largest firms (in terms of the total amount of dispatchable generation that they own) constitute the set, $\mathcal{I}$. The remaining firms are aggregated into a competitive fringe, which commits to a supply function, which we denote as $\sigma(p)$. $\sigma(p)$ represents the MW of supply from the competitive fringe as a function of the energy price, p. **Table 1** summarizes the capacities of the three dispatchable generation technologies that are owned by the eight largest strategic firms and the competitive fringe. The table shows that the market is asymmetric, with the three largest firms holding a disproportionate share of natural-gas-fired generation. The 32.5 GW of dispatchable generation that is owned by the competitive fringe is assumed to be offered into the market at cost, *i.e.*, we have that $\sigma(p)$ is equal to the inverse of the marginal-cost function of the competitive fringe.

Table 1: Capacities (GW) of dispatchable generation technologies that are owned by strategic firms and competitive fringe

Firm	Coal	Natural Gas	Oil
TEPCO F&P	3.2	29.3	8.7
Chubu	4.1	19.1	2.3
Kansai	1.8	10.2	7.5
Tohoku	3.2	7.4	1.7
Kyushu	2.5	4.6	3.3
J-Power	8.4	0.0	0.0
Chugoku	2.6	2.4	2.8
Hokuriku	2.9	0.0	1.5
Competitive Fringe	18.2	7.9	6.4

Fourth, we combine technology-specific benchmark generator heat rates[4] with average FY2017 fuel prices[5] to estimate the marginal cost of each dispatchable generator. This gives a stepped marginal-cost function for each firm, which we linearize using linear regression. Specifically, we discretize each firm's stepped marginal-cost function from 0 to its aggregate capacity using 10-MW increments and use ordinary least squares to estimate the slope of a linear approximation of the cost function, assuming a fixed intercept. **Fig. 1** illustrates the stepped marginal-cost function and linear approximation for one of the firms, which holds a total of 41.1 GW of generating capacity.

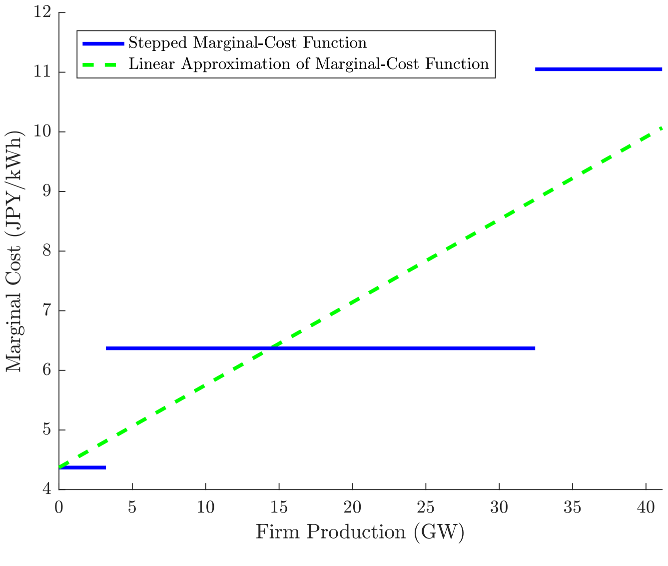

Figure 1: Estimate and linear approximation of marginal-cost function for one firm

Once an SFE is computed, the supply functions of the eight strategic firms and competitive fringe are added to derive an aggregate supply function. Aggregate supply is intersected with each hour's residual load to determine the hourly market-clearing price, production levels of the

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[3] https://www.enecho.meti.go.jp/statistics/electric_power/ep002

[4] https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/

[5] https://www.customs.go.jp/toukei/info/index.htm

eight strategic firms and competitive fringe (from which we determine the production level of each generating unit), firms' profits, and carbon emissions from the electricity sector. Carbon emissions are computed from production levels by combining the heat rate of each generation technology with the average carbon content of each generation fuel. We use the same SFE for each hour of each year, meaning that we neglect scheduled or planned generator outages, which can understate the potential exercise of market power by the eight strategic firms [4]. Currently, the Japanese wholesale electricity market allows a maximum offer price of 1000 JPY/kWh, and we set $\bar{p}$ equal to this value. As is discussed in Section 4.1, this value of $\bar{p}$ overestimates the exercise of market power. Thus, we examine an additional set of cases with a lower value of $\bar{p}$.

We examine three sets of policy cases. The first is a business-as-usual (BAU) case, wherein the FY2017 market and policy conditions are modeled. The second is a set of cases with explicit carbon pricing that is imposed on the electricity industry. We assume Pigouvian carbon-tax rates of 46.08 USD/t and 134.64 USD/t, which correspond to the social cost of carbon under central- and high-impact cases [32].[6] We use the average FY2017 exchange rate of 112.19 JPY/USD for currency conversion. The carbon-tax cases are modeled by accounting for the carbon tax in estimating firms' marginal-cost functions.

The other set of cases assume that a renewable portfolio standard (RPS) is used to encourage the use of zero-carbon electricity-generation technologies. One RPS case assumes that Japan achieves its 2030 target of increasing solar and wind penetration by factors of 2 and 7, respectively, relative to their FY2017 levels. The other RPS case assumes that Japan achieves its 2050 target of these penetrations increasing by factors of 4 and 14, respectively. These cases are modeled by scaling hourly solar and wind generation using multiplicative factors.

We contrast market outcomes under SFE to a case of perfect competition. Perfect competition is modeled by assuming that all firms offer their generation into the market at marginal cost, *i.e.*, we have that $q_i(p) = c_i'^{-1}(q)$, $\forall i \in \mathcal{I}$. These supply functions are combined with the supply function of the competitive fringe to compute aggregate supply, from which prices, production quantities, and carbon emissions are computed.

4. Case-Study Results

4.1. Case-Study Calibration

Fig. 2 is a scatterplot of price/quantity data that are generated by the SFE model in the BAU case and in the corresponding *actual* historical FY2017 data. The figure shows that our model overestimates the exercise of market power by the strategic firms (in the historical data). Empirical analyses of wholesale electricity markets demonstrate such limited exercise of market power, especially if a market is in its relative infancy. This phenomenon is observed in Texas's wholesale electricity market and may be due to learning by firms during the early stage of market restructuring [18]. Analysis of California's wholesale electricity market [28] suggests that firms may begin to increase their exercise market power as they gain familiarity with the market.

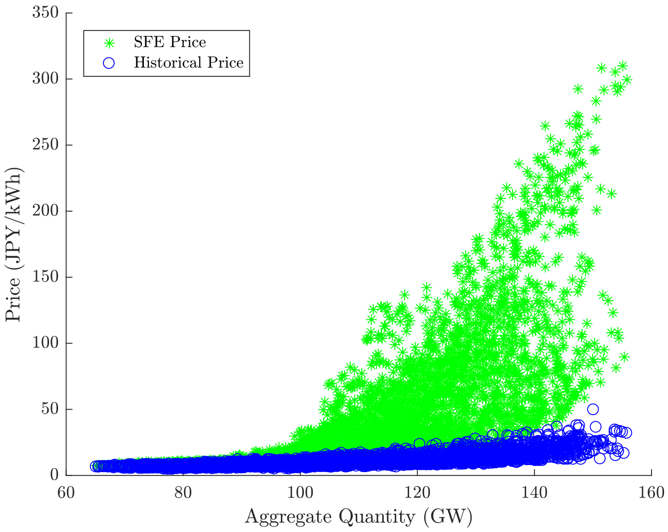

Figure 2: Scatterplot of price/quantity data for BAU-SFE using $\bar{p} = 1000$ and corresponding historical data

Fig. 3 shows the same type of scatterplot that is shown in **Fig. 2**, except with a lower value of $\bar{p} = 100$. **Fig. 3** shows a much better fit to the historical price/quantity data. As such, we examine cases with $\bar{p} = 100$ and $\bar{p} = 1000$. The former reflects behavior as is observed currently in the Japanese wholesale electricity market and the latter reflects possible future behavior, once firms gain additional familiarity with the market.

4.2. Energy Mix

Table 2 summarizes the mix of energy that is provided by the different generation technologies over the course of the year that is modeled. Under perfect competition, a carbon tax yields significant reductions in coal-fired generation compared to the BAU case. This reduction is due to a cost reversal between coal and natural gas, whereby natural-gas-fired generators are operated as baseload units and coal-fired units operate only when other generating capacity is exhausted. So long as the carbon-tax rate is sufficiently high to cause such a price reversal, the actual carbon price does not impact the mix of resources that is operated to serve electricity demand. This result is reflected in the fact that the energy mix with the two carbon-tax rates that we consider are identical under perfect competition (*cf.* **Table 2**).

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[6] The study from which the social cost of carbon are obtained [32] reports these values in 2007 USD. We convert these values to 2017 USD using consumer price index, as reported by U.S. Bureau of Labor Statistics.

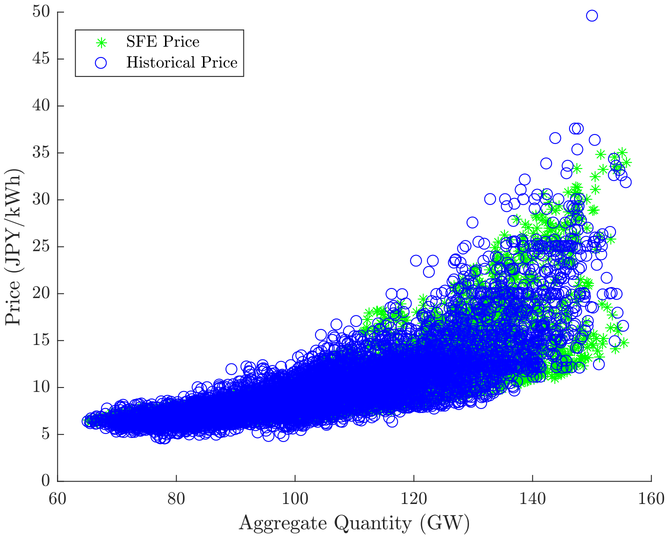

Figure 3: Scatterplot of price/quantity data for BAU-SFE using $\bar{p} = 100$ and corresponding historical data

With the exercise of market power (*i.e.*, the cases with $\bar{p} = 100$ and $\bar{p} = 1000$), carbon taxes do not yield the same extent of shifting from coal- to natural-gas-fired generation. This muted effect of a carbon tax is because a large portion of the natural-gas-fired fleet is owned and operated by the two largest firms (*cf.* **Table 1**). For instance, with $\bar{p} = 100$ during hours with the market-clearing price below 20 JPY/kWh, the two largest firms produce about 10 GW each, despite their holding about 65 GW of generating capacity total. 50 GW of the capacity that the two largest firms own is natural-gas-fired, meaning that about 30 GW total of natural-gas-fired generation is being withheld from the market through the strategic behavior of the two largest firms. By withdrawing this capacity from the market, higher-priced (coal-fired) clears the market, which increases the market-clearing price of energy and the profits of the two largest (and other) firms.

4.3. Carbon Emissions

Table 3 summarizes total annual CO_2 emissions from the different generation technologies over the course of the year that is modeled. As expected from the results that are shown in **Table 2**, under perfect competition, a carbon tax can yield significant emissions reductions compared to BAU. Moreover, carbon-emission reductions are identical with the two carbon-tax rates that we examine under perfect competition. The exercise of market power results in muted carbon-emissions reductions that are between those that are achieved through the two RPS targets. Thus, the combination of market power and a highly asymmetric market structure yields a muted benefit from a carbon tax. Production-cost models or other methodologies to study carbon policy may not reveal such findings [7].

Table 2: Total annual energy mix (TWh) between generation technologies

Case	Coal	Natural Gas	Oil	Wind	Solar
BAU					
Perfect Competition	410	222	0	7	51
$\bar{p} = 100$	391	220	22	7	51
$\bar{p} = 1000$	387	194	51	7	51
\$46.08/t Tax					
Perfect Competition	26	607	0	7	51
$\bar{p} = 100$	243	370	19	7	51
$\bar{p} = 1000$	260	314	59	7	51
\$134.64/t Tax					
Perfect Competition	26	607	0	7	51
$\bar{p} = 100$	230	381	21	7	51
$\bar{p} = 1000$	241	338	54	7	51
RPS 2030					
Perfect Competition	391	151	0	46	102
$\bar{p} = 100$	364	165	12	46	102
$\bar{p} = 1000$	360	147	35	46	102
RPS 2050					
Perfect Competition	322	94	0	89	185
$\bar{p} = 100$	296	112	7	89	185
$\bar{p} = 1000$	291	102	22	89	185

5. Conclusions and Policy Implications

We develop an SFE-based framework with which to examine the effects of carbon policy on wholesale electricity markets. We apply our model to a case study that is based on Japan's electricity industry, which is concentrated and highly asymmetric. Our case study shows that carbon pricing, which has theoretically desirable properties, can have muted effects in reducing carbon emissions in an imperfect market. Indeed, in the presence of market power, the more-aggressive RPS case (which corresponds to Japan's 2050 targets) yields greater emissions reductions in our case study than the two carbon-tax cases do. This result runs counter to other analyses [7] that neglect market power and find that RPS is an inefficient policy mechanism through which to achieve decarbonization goals. Our finding of the limited benefits of carbon pricing is due to the specific structure of Japan's electricity market. Natural-gas-fired generators are owned disproportionately by the largest firms, which have the potential to exercise market power by withdrawing their capacity from the market. Thus, this result is specific to the structure of Japan's market and depends upon the extent to which firms exercise market power. As such, our results should be not generalized to other markets or settings. Nonetheless,

Table 3: Total annual carbon emissions (MT) from generation technologies

Case	Coal	Natural Gas	Oil	Total
BAU				
Perfect Competition	338	78	0	416
$\bar{p} = 100$	323	77	14	401
$\bar{p} = 1000$	320	68	34	422
\$46.08/t Tax				
Perfect Competition	21	212	0	233
$\bar{p} = 100$	200	129	13	342
$\bar{p} = 1000$	214	110	39	363
\$134.64/t Tax				
Perfect Competition	21	212	0	233
$\bar{p} = 100$	190	133	14	337
$\bar{p} = 1000$	199	118	36	353
RPS 2030				
Perfect Competition	323	53	0	376
$\bar{p} = 100$	301	58	8	367
$\bar{p} = 1000$	297	51	23	371
RPS 2050				
Perfect Competition	266	33	0	299
$\bar{p} = 100$	244	39	5	288
$\bar{p} = 1000$	240	36	14	290

our approach to studying this problem could be applied in other contexts. Moreover, our work demonstrates the limitations of relying upon models that neglect market power or other market failures in examining and comparing policy options.

Our model abstracts-away some technical details of electricity systems, which must be excluded for purposes of computational tractability. This includes generator-operating (*e.g.*, unit-commitment and ramping) and network (*e.g.*, transmission and distribution) constraints. The potential exercise of market power could be exacerbated by such constraints, because certain generators may not be able to serve demand under certain conditions. On the other hand, we neglect forward contracting and the price-elasticity of demand, which can reduce the exercise of market power [4, 33]. Price-elastic demand can impact carbon emissions through a substitution or other effects [12]. Substitution effects are more pronounced over the long-term, as opposed to the short-term analysis that we conduct. Our SFE calculations assume that firms believe that there is a non-zero probability that capacity constraints become binding (*cf.* Appendix A). This assumption may overstate the exercise of market power as well.

Another important limitation of our study is that it is a short-run analysis, whereby we hold the generation-capacity mix fixed. A long-term analysis, that endogenizes capacity-investment and -retirement decisions, may paint a more complete picture of the costs of and tradeoffs between different carbon-mitigation policies. For instance, our work demonstrates that in the presence of market power, a carbon tax can be a relatively inefficient carbon-mitigation policy during the short-run. However, a carbon tax may yield more efficient long-run capacity-investment and -retirement decisions than what is achieved by a policy mandate, such as an RPS. Although such a long-run analysis is beyond the scope of our analysis, it is a worthwhile topic for future research.

Despite these limitations of our work, policy implications can be drawn from our findings. Chief amongst these, the importance of market monitoring and other measures to mitigate the exercise of market power is clear. The exercise of market power can be welfare-diminishing absent carbon policy. Our work shows that with consideration of carbon-mitigation policy, market power can become a more important issue. As such, co-ordination between market monitors and bodies that implement carbon policy is important. As aforementioned, supplementing our work with a long-term analysis that endogenizes capacity investments and retirements would provide a more complete picture of the interactions between and efficiency implications of market power and carbon policy. Nevertheless, we anticipate that market power will be an important issue, even within a long-term context.

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Appendix A. Computation of SFE

Computing an SFE requires solving (4), $\forall i \in \mathcal{I}$ simultaneously. Equilibrium computation raises a number of difficulties. For one, there is no guarantee of a unique SFE, which raises the question of which equilibrium to analyze. Second, it can be difficult to ensure that solutions to (4) yield monotone supply functions, which is required by market rules and for technical reasons [34]. As such, it is common for applications of SFE to make simplifying assumptions, such as symmetric firms or linear marginal-cost and supply functions [35].

We take a different approach, which requires a price cap and a non-zero probability that demand may be high enough that all but one firm is capacity constrained [30, 36]. Under these assumptions (and the others that are discussed in Section 2), Holmberg [36] characterizes a unique SFE. The unique SFE has the property that once demand is high enough for all but one firm to be capacity constrained, the unconstrained firm behaves as a residual monopolist and offers its remaining capacity at the price cap. As such, this SFE is the least competitive, in the sense that prices and firm profits are the highest.

To compute the SFE that Holmberg [36] characterizes, we assume without loss of generality that $\mathcal{I}$ is an ordered set and that the firms are in decreasing order of their total capacities (*i.e.*, firm 1 has the most capacity and firm $|\mathcal{I}|$ the least capacity). Next, we represent an SFE by the vector, $\theta = (\Delta S_1, p_3, \cdots, p_{|\mathcal{I}|})$. ΔS_1 is the amount of capacity that firm 1 offers at the price cap (*i.e.*, when it is a residual monopolist, because all of its rival firms are capacitated). For all $i = 3, \ldots, |\mathcal{I}|$, p_i is the price at which firm i's capacity constraint becomes binding. By definition, firm 2's capacity constraint becomes binding at the price cap, $\bar{p}$. Next, we define $\Gamma(\theta)$ as the price at which one of the supply functions violates the monotonicity requirement, *i.e.*, we have that $\Gamma(\theta)$ is the highest value at which $\exists i \in \mathcal{I}$ such that $q_i'(\Gamma(\theta)) < 0$.

In theory, there should exist an optimal parameter vector, θ^*, which gives $\Gamma(\theta^*) = c_1'(0)$. In practice, finding such a θ^* may not be possible, because differential equations (4), which characterize optimal supply functions for the firms, must be solved using numerical integration, which introduces numerical errors. As such, we approximate an SFE by solving the following optimization problem:

$$\min_{\theta} \Gamma(\theta) \tag{A.1}$$

$$\text{s.t.} \, c_1'(0) \leq p_{|\mathcal{I}|} \leq p_{|\mathcal{I}|-1} \leq \cdots \leq p_3 \leq \bar{p} \tag{A.2}$$

$$\Delta S_1 \geq 0. \tag{A.3}$$

By solving (A.1)–(A.3), our goal is to find a near-optimal, $\tilde{\theta}$, which yields $\Gamma(\tilde{\theta}) \approx c_1'(0)$. We solve (A.1)–(A.3) using the derivative-free Nelder-Mead algorithm. This is because computing the partial derivatives of $\Gamma(\theta)$ is expensive, whereas the value of $\Gamma(\theta)$ can be computed by numerically integrating (4), $\forall i \in \mathcal{I}$ until one of the supply functions violates the monotonicity requirement. Nelder-Mead algorithm and numerical integration of (4) are implemented in our case study using SciPy 1.0.0 package in Python 2.7.

Yagi [37] and Yagi and Sioshansi [30] provide additional details on how the SFE model is implemented and equilibria are calculated.