

Cleaner but volatile energy? The effect of coal plant retirement on market competition in the wholesale electricity market

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Abstract

U.S. wholesale electricity industry is undergoing a major transformation due to increasing retirements of coal-fired power plants which will be replaced by natural gas and renewable energy. This environmentally desirable transition towards cleaner energy could change the competitiveness of the industry, an important element that must be considered when assessing the real benefit of the clean energy. This paper studies how the strategic competition and market outcomes would change in a newly transformed wholesale electricity market, focusing mainly on a specific feature of the clean energy: the volatility of its input costs. Unlike coal generation that has consistently low and stable generation cost, the opportunity cost of natural gas and renewable generation is volatile, being sensitive to the spot gas market condition and the weather. In this respect, the retirement of coal-fired plants could result in replacing the low-cost generation with potentially high-cost generation, making proportionally more of the industry's generation susceptible to possible input cost shock. Using data from the New England wholesale electricity market, we adopt a structural analysis to examine the change in competition between firms and the resulting market outcomes in a counterfactual situation where all the planned and ongoing retirements of coal plants have taken place. Moreover, we can also analyze how the effect of retirement differs with the presence of input cost shocks because the local natural gas prices in New England are highly volatile. We find that the retirement would cause up to 20 % increases in wholesale electricity prices as a result of increased market power, especially when the gas generators experience larger input cost shocks due to high gas prices. Also, the firm-level analysis shows that the result is mostly driven by the strategic withholding (exercise of market power) by the large-scaled, gas-intensive firms that are not directly affected by the retirement.

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1 Introduction

The conventional baseload generation capacity – coal and nuclear power – is rapidly retiring from the grid, and the natural gas and renewable energy are emerging as a new source of baseload generation in the U.S. wholesale electricity market. Broadly two factors are responsible for this change. First is the tight environmental regulation that raises the emissions cost of highly-polluting coal generation.¹ Second and most important factor is the economic concerns. Due to a significant drop in the price of natural gas, which is mainly driven by the shale gas boom, coal plants are losing its cost advantage over gas-fired power plants.² Declining gas prices are making these baseload generation less efficient, and they are driven out of the industry as a result.

While the coal plant retirement draws attention with respect to environmental benefits or grid stability, this paper focuses on the competition side of this transition. That is, will the changing grid condition – into a heavily gas-concentrated industry – affect the way that firms compete in the wholesale electricity market? This question is particularly relevant when considering a specific feature of the clean energy; the volatility of input costs. Unlike coal, the price of which is always low and stable, gas prices are subject to potential shocks as the gas price (supply) is sensitive to the condition of infrastructure (e.g., pipeline).³ Renewable energy is also prone to the input cost volatility due to its intermittent nature; when they are not available abruptly, a high-cost fringe (reserve) generator needs to replace the zero-cost renewable generation.

In this respect, retirement of coal-fired plant results in replacing a consistently low-cost generation with the generation having a lower but more volatile cost which could increase up to a level several times higher. Therefore, the industry's transition towards cleaner energy sources is making the industry more vulnerable to the input cost shock. It is important to study how the competition and the market outcome will be different when such input cost shock occurs in the transformed industry, compared to when the industry was composed of relatively balanced generation mix including stable baseload generation. For a comprehensive assessment of the true benefit and cost of the clean energy, a thorough analysis of the competition, considering the volatile nature of its production cost, is necessary.

I study this in the context of the New England wholesale electricity market which is one

¹About 40 % of carbon dioxide emissions in the U.S. originate from electricity generation (Goulder et.al, 2014), therefore the primary goal of environmental regulations of energy sector is to cut the use of highly-polluting fossil fuels like coal and to increase the use of less-polluting natural gas and renewable source for electricity generation. For example, EPA's *Clean Power Plan*, which is suspended now, set ambitious goals to reduce emissions from heavy-polluting fossil fuel power plants.

²As the low-cost gas generators mostly clears the electricity market, the market price has also become consistently low. For this reason, the nuclear generation is increasingly retiring from the grid as the low electricity price is not enough for them to recover the huge fixed cost of operating.

³Gas must be delivered through pipelines at the time of use, which makes its spot prices sensitive to congestion in the pipeline.

of the several electricity markets in the U.S. that frequently experience a surge in gas prices. The pipeline that transports gas to the New England area is limited in capacity and thus frequently congested, especially in winters. The congestion results in a sharp increase in gas prices that leads to an increase in the cost of gas-fired generators. Despite having a weak pipeline infrastructure, the New England grid is awaiting retirements of several large coal and nuclear plants, which will be replaced by the gas and renewable generation that are planned for construction.⁴

To examine the change in the competition and market power resulting from the retirement, I implement a counterfactual analysis that is based on the model of quantity competition. I simulate the market outcome (price of the electricity) and firm-level production decisions under the reconstructed market conditions, where all the planned power plant retirements take place and are replaced with a hypothetical gas-fired plant of a same capacity. This is to control for the capacity at the industry and firm-level, which are known to affect the competition in electricity market; only the composition of generation technology are changed by the retirement. Such counterfactual situation mimics the market environment that is likely in the near future.

Counterfactual analysis is suitable for our analysis for several reasons. In the data, plant retirements occur sporadically over time, and the capacity of each retired plant is too small to have a significant effect on the market outcome, making the event study type of analysis not so attractive. Moreover, because the retirement of a plant affects the entire industry, finding a proper control group unaffected by the retirement within this industry is not possible. Finding another electricity market that has similar feature (types of firms, for example) as New England market is challenging as well. Also, predicting a counterfactual generation pattern from the generation regression estimates, as in Davis and Hausman (2016), is not suitable in our case when the merit order and the cost distribution is significantly disturbed in the counterfactual situation. Finally, having a structural model describing the strategic decisions of firms is more suitable for the analysis of competition between firms.

The counterfactual outcomes are simulated under two different forms of competition: perfect competition and Cournot competition. Wholesale electricity market is organized as auctions, but simulating the counterfactual equilibrium (i.e., supply function equilibrium (SFE)) in the auction setup is difficult due to multiple equilibria problem. Therefore, as commonly used in the electricity market studies, I instead simulated competitive and Cournot outcomes exploiting the findings of Klemperer and Meyer (1989) that counterfactual SFE equilibrium is bound by competitive and Cournot equilibrium (Klemperer and

⁴With no viable plans to expand the capacity of the pipeline, the region still faces the threat of gas price shocks in the future.

Meyer, 1989).⁵

Moreover, comparing the outcomes simulated under two different market structures more precisely shows how the strategic interaction changes due to retirement, and the part of outcome differences attributed to the competition. While the Cournot model give production decisions that accounts for strategic consideration, the competitive equilibrium captures only the production change resulting from the merit order change (industry supply curve change) arising from the retirement, absent of competition. Such outcome changes that naturally arise due to retirement must be accounted for, especially in our analysis where cost and merit order change is the central feature of the retirement. Then, the change in competition and the degree of market power can be measured by comparing how much the strategic prices (or market quantity) change, relative to the change in competitive prices (or quantity).

An important part of the counterfactual is to allow for marginal cost to vary according to the changes in the gas prices. This part is especially important as the primary variable changing with the retirement event is the distribution of costs. To tackle this, I use the data of actual days when gas prices surged when simulating equilibrium. By leveraging rich bidding data available at a generator level and at daily frequency, I estimate firm-unit specific marginal costs and use them in characterizing the industry-level and firm-level marginal cost curves.

The result shows that the impact of retirement is most salient in low-demand (off-peak) sample, and when the gas price is high. That is, the unilateral market power – measured by how strategic price departs from the competitive benchmark – increases more during low-demand than in high-demand, and when gas prices are higher. These are highly correlated with the extent of cost disturbance, relative to what is observed before, as well as the price responsiveness of the non-strategic fringe supply. The retirement induced cost distribution change results in giving more ability to those large scaled firms not directly affected by the retirement and highly gas-intensive in their generation to exercise market power. As a result, the market price increases on average up to 20 % compared to the competitive price. However, the result must be interpreted with caution when considering that this is the upper bound of the likely impact. Indeed, small increase in market power simulated for high-demand hours implies that we may actually see a decline in market power in this case. Moreover, a significant decrease in competitive prices during peak hours indicate that if the market performed close to competitive, the retirement could be welfare enhancing.

This paper contributes to the literature that studies the competition in the wholesale electricity market. The methodology used in this paper is close to that of Bushnell, Mansur, and Saravia (2008) where they examined the impact of vertical arrangements on competi-

⁵Since Cournot equilibrium is similar to actual supply function equilibrium outcome especially during competitive peak-hours, some studies use only the Cournot model for the counterfactual analysis (Ito and Reguant (2016) for example.)

tion in the wholesale electricity market. Regarding the topic similarity, this paper is related to Davis and Hausman (2016) in that it considers the market impact of closure or retirement of power plants. This paper is distinguished from theirs in that it addresses more counterfactual studies involving cost shock events, and that it focuses more on the competitive effects.

2 Institutional Background

2.1 The retirement of baseload power plants and the changing market environment

Coal-fired power plants and nuclear power plants are considered the base load generation, since they supply constant amount of electricity over time without much interruption. Although the primary focus of this paper is on the coal-fired plants, I also include the retirements of nuclear power plants in the analysis. These *baseload* plants are characterized by having a large start-up cost which makes it costly to adjust the generation flexibly over time.

A large number of baseload power plants have retired from the U.S. wholesale electricity market over the past several years. On the national level, coal-fired capacity available for operation has dropped by approximately 47.2 GW between 2011 and 2016, which is equivalent to a 15 % reduction in the coal-fired generation over five years period (EIA, 2017). Nuclear power plants which account for almost 20 % of generation in the U.S. are also moving towards a path of retiring from the grid. About 25 % of the nuclear generation capacity currently operating in the U.S. haven't renewed their license, revealing their intention to retire from generation.⁶ Given that more coal and nuclear generation is retired than built, and as natural gas and renewable energy gain market share, the share of coal and nuclear generation together now consist only 11 % of the total generation capacity in the U.S. wholesale electricity market (EIA, 2017 *Annual Energy Outlook*).

Several factors led to an increase in the baseload plant retirements. First is the rising environmental costs incurred to meet the stringent environmental regulation, since the highly polluting coal-fired plants bear large emissions costs.⁷ However, a more important factor that expedites the retirement is the decline in natural gas prices due to the U.S. shale gas boom which started from the late 2000s. The significant drop in the gas price made it more expensive to generate electricity with coal than with gas, and the coal-fired plants are losing its cost advantage over gas-fired plants. Moreover, the market price for electricity decreased substantially, even during peak hours, because the low-cost gas-fired generator clears the

⁶<https://www.eia.gov/todayinenergy/detail.php?id=31192>

⁷EPA regulations such as Mercury and Air Toxics Standards (MATS) and Cross-state Air Pollution Rule (CSAPR) affect coal plants.

Fuel	participating generators		producing generators	
	(1) capacity (MW)	(2) % of total capacity	(3) capacity (MW)	(4) % of total capacity
gas	10,735	31.81	8,542	52.37
gas/oil dual	6,195	18.36	1,352	8.29
oil	4,384	12.99	0	0
coal	2,314	6.86	1,060	6.5
nuclear	4,452	13.22	4,462	27.36
hydro	3,066	9.09	446	2.73
other	268	0.79	228	1.17
total	31,424	100	16,090	100

Notes: Sample day in the winter period of 2012 is used. The capacity of *participating generators* is calculated by adding up the capacities of generating assets that bid in the day-ahead wholesale electricity auction. The capacity of *producing generators* is the sum of capacities of the assets that are dispatched (accepted in the auction) at the market clearing (wholesale) electricity price of \$40/MWh which is about the average price of a normal day with a moderate level of market demand. The second categorization excludes assets that bid substantially higher than the ex-post market price, which could be either high-cost generating units like oil-fired units or reserve units.

Table 1: Summary of Generation Capacity by Fuel Type in the New England Market)

market most of the time. As a result of the consistently low electricity prices, the revenues of the baseload generators are not enough to cover their operating and fixed costs of generation (ISO-NE, 2016: power plant retirements, EIA- today in energy). Such profit loss coming from the low electricity price is the main driver of the retirement of nuclear power plants (Davis and Hausman, 2016).

2.2 Baseload Plant Retirements in the New England Wholesale Electricity Market

Although the New England wholesale electricity market has a large share of gas generation, baseload generation capacity also takes up a significant part of the generation. Table 1 summarizes the capacities of power plants in New England.⁸ Columns (1) and (2) summarizes the capacities by fuel types of generators actively participating (bidding) in the market every day, whereas columns (3) and (4) summarizes the capacities of those actively generating electricity in the market (by being accepted in the auction).

Gas-fired generation (including gas/dual generators) consists about 50 % of the total capacity of participating generators. The percentage share of the baseload generation – including coal-fired and nuclear power generation – is about 20 % of the participating generator

⁸This summary is done for a representative day selected from the sample. I used information obtained from the bidding data of $t = 60$ (October, 30, 2012) in my sample. I used the bidding data instead of the external data set that reports the generating capacity because this data set includes generators that are prepared for emergency operation (reserved capacity). Here I summarized capacities of those generators that actively bid and produce electricity in the market. Note that these capacities are different from the nameplate capacity of the generator. Name plate capacities would be larger than the capacities reported here in Table 1.

Plant Name	Capacity (MW)	Fuel type	Date of shutdown
Norwalk Harbor Station	342	oil	June, 2013
Salem Harbor Station	749	coal/oil	June, 2014
Mount Tom Station	143	coal	Oct. 2014
Vermont Yankee	604	nuclear	Dec., 2014
Brayton Point Station	1,535	coal/oil	May, 2017
Pilgrim Nuclear Station	677	nuclear	planned for 2019

Table 2: Major Power Plant Retirements in New England

capacity, which is smaller compared to the that of gas-fired generation. However, once we restrict the generation to the ones actively producing electricity, the percentage share of the baseloads increases to about 34 % which is quite large.⁹ Given the considerable share of the baseload generation in this market, we expect the retirements of these plants to have quite significant effects on market outcomes.

Indeed, the New England wholesale electricity market is undergoing, and expecting some major baseload plant retirements. More than 4,200 MW of the market’s baseload generation – the size equivalent to almost 15 % of the total capacity as of 2016 – have retired or expected to retire by 2020. Table 2 presents some of the major power plant retirements. Retired capacity mostly consists of coal, nuclear and some oil plants. Each retirement – small in size relative to the total market capacity – will not pose a significant threat to the market operation — in other words, the grid reliability — as the grid is prepared with enough gas generation (reserve capacity) to fill in the lost baseload generation.¹⁰

In the long-run, the retired generation will be replaced primarily by the gas-fired plants and partially by the renewable generation.¹¹ Once the retirement and its replacement is completed, the New England market’s reliance on the gas generation will further increase, from having 45 % to up to 56 % of generation coming from gas (projected ratio by 2025, *ISO-NE report* in 2017). This implies that now the gas-fired generation would serve the baseload generation which used to be served by the coal and nuclear plants.

⁹Once we further restrict the sample to the off-peak (low demand) hours, the share of the baseload generation grows even larger (though this information is omitted from Table 1) which is not so surprising as most of the off-peak generation comes from the baseloads.

¹⁰Nevertheless, retirement can have some immediate effects on market prices and production efficiency since it leads to an inward shift of the industry supply curve. This was the primary focus of Davis and Hausman (2016) where they study the market impact of an abrupt closure of the nuclear power plant in California wholesale electricity market. Whether the shift of the industry supply curve has an impact on market outcome depends on the level difference between marginal costs of the capacity being removed and the capacity that fills in. When the zero-cost nuclear plants are removed from the grid, the generation having marginal costs higher than that of nuclear plants (positive marginal costs) are pushed inward to replace them and as a result the electricity price increases, given the same level of aggregate market demand.

¹¹According to ISO-New England, most of the ongoing capacity construction will be gas-fired generation. For example, the firm that operates the *Salem Harbor* Station, a coal-fired plant that retired in 2014, is converting the plant site into a natural gas-fired plant.

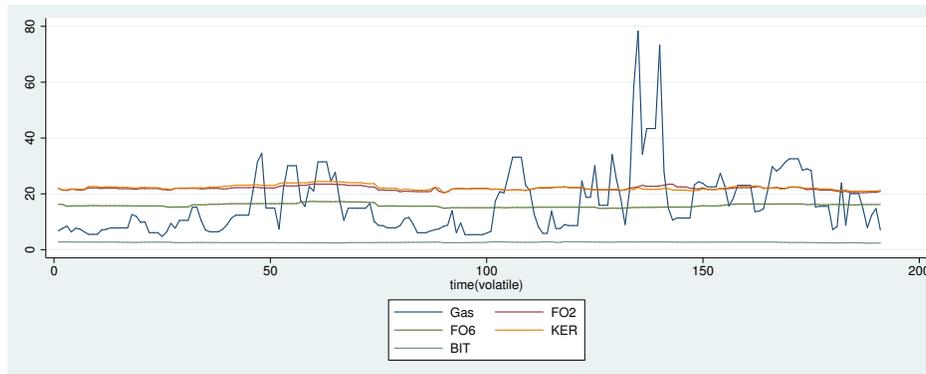


Figure 1: Spot prices of fossil fuels

2.3 The natural gas price shock and the increase in the input cost of generation

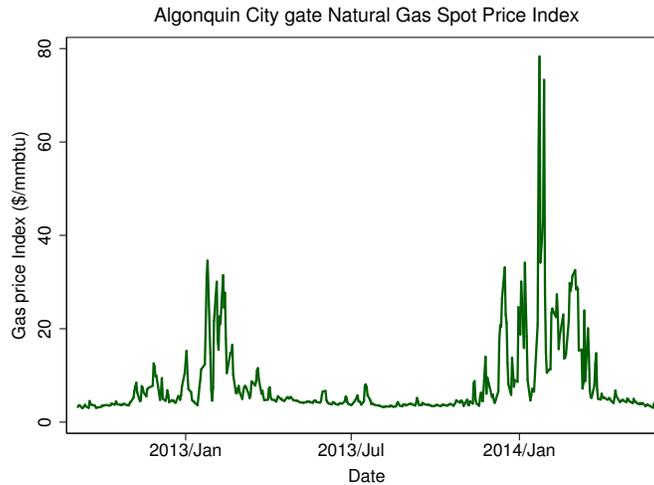
The level and volatility differences of fuel prices Since the fuel cost – the part of generation cost spent on purchasing fuel – takes up the largest part of the marginal cost of electricity generation, marginal cost is sensitive to any changes in spot prices of fuels. That is, an increase in the fuel prices, as well as the increased volatility of fuel prices will be reflected in the marginal cost, affecting both the level and volatility of marginal costs.¹²

There are some important differences in the levels and volatility of prices of different fuels, which can be observed from the time series plot of spot prices shown in Figure 1. The price of coal has always been lower than the price of other fossil fuels such as natural gas and petroleum products. Natural gas prices had been expensive in the past, but decreased steadily since the shale gas boom. As a result, prices of coal and natural gas have been similar over the past decade. Once we factor in the emissions costs of coal-fired plants that are larger than those of gas-fired plants, coal generation could become more expensive than the gas-fired generation.

Secondly, in terms of price volatility, there is a clear difference between natural gas and other fossil fuels. Local gas prices could become extremely volatile primarily due to the pipeline congestion. Some regions in Northeast of the U.S. where the pipeline network is outdated and limited in capacity frequently experience spikes in local natural gas prices, especially in winters when gas demand increases due to increased use of gas for the residential heating. On the other hand, coal prices have not changed much over time and across regions, having almost no fluctuations.

New England is the region that experiences the most severe and frequent natural gas price shocks. As shown in Figure 2, natural gas prices at the city gate in New England

¹²The fuel cost part is represented as heat rate (the physical efficiency of a generator which measures how efficiently a generator can convert the fuel into energy) multiplied by the price of the fuel that a generator uses, i.e. heat rate · fuel price.



Notes: Natural gas price index plotted against date. Source: *Natural Gas Intelligence*

Figure 2: Gas Spot Price Shocks in New England: Winters of 2013 and 2014

reached up to \$ 76/MMBtu and significantly fluctuated over time in the winters of 2013 and 2014. This was not a one-time event, but rather becoming persistent; the gas prices again went up to a record high level of \$ 82.75/MMbtu recently in the winter of 2018.¹³ When compared to the normal gas price level – \$ 4 /MMbtu – when the pipeline congestion problem does not occur, the extent and volatility of gas price shocks were quite severe.

Table 3 summarizes the number of days, and percentage out of total days, in years 2013 and 2014 when gas prices rose above the usual level of \$ 4/mmbtu. In total, almost 30 % of days in the sample experienced mild to severe gas price shocks. Therefore, while such event is not highly likely, it cannot be disregarded at the same time given a quite frequent occurrence.

3 The plant retirement, cost distribution and the competition

There are broadly two factors that may affect the competition between firms, especially in the context of the wholesale electricity market. First is the distribution of marginal costs of electricity generation since the cost of production relative to others governs a firm’s ability to exercise market power. In other words, if the distribution of marginal costs differ across days, it is reasonable to expect the degree of competition to differ as well.¹⁴ Second impor-

¹³Source: 2014 price comes from the author’s data obtained from the Natural Gas intelligence Inc. and 2018 price information is taken from Reuters (<https://www.reuters.com/article/us-usa-weather-energy-prices/frigid-weather-sends-heating-prices-soaring-as-energy-usage-spikes-idUSKBN1EU1IR>)

¹⁴This conditions on the fact that the mean of the costs changes together with the distribution of costs. Bergstrom and Varian (1985) shows that the equilibrium outcome is invariant to the distribution of costs as

Days with gas price shock	year	total	between \$10-\$20/mmbtu	between \$20-\$30/mmbtu	above \$30/mmbtu
N	2013	102	29	6	8
	2014	112	30	37	16
% (N/365)	2013	27.9 %	8%	1.6 %	2.2 %
	2014	30.7 %	8.2 %	10.1 %	4.4 %

Table 3: Summary of days with above normal gas prices (gas price shock)

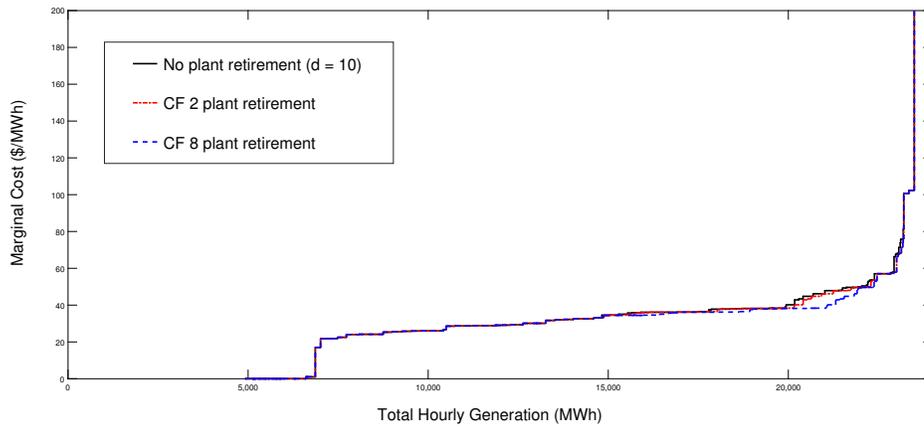
tant factor is the market demand, especially regarding the price elasticity of demand which restricts firms' ability to increase prices. However, due to specific feature of the wholesale electricity market, the demand for electricity tends to be almost perfectly inelastic, making the elasticity not of our concern in the analysis. Nevertheless, the aggregate *level* of demand is important for determining the set of strategic firms that are effective competitors, as well as for locating the part of the supply curve that is relevant for the analysis of market equilibrium.

Input cost shock and the marginal cost distribution The composition of generation assets is heterogeneous both at the industry-level and at the firm-level; generators with different types of fuels such as coal, nuclear, oil, and gas exist in the industry. Therefore, a substantial increase of the gas price would affect the cost of generation asymmetrically by increasing the input cost of only the gas-fired generators, thereby disrupts the industry-level distribution of marginal costs.

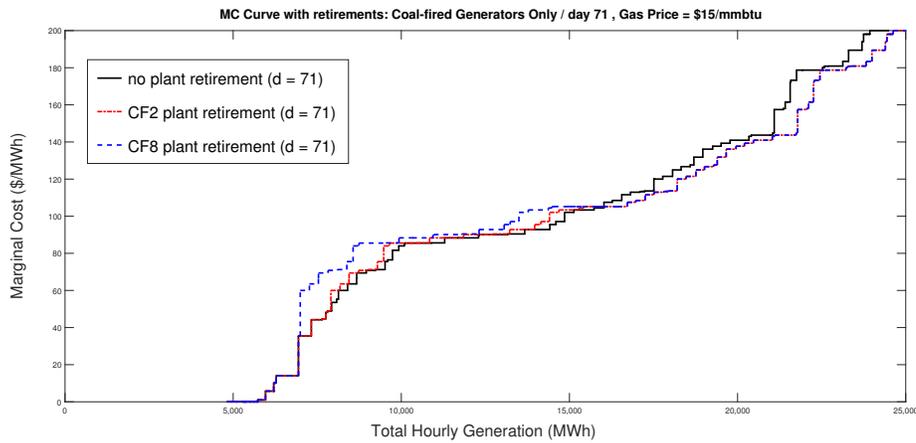
The effect of plant retirement on the industry-level marginal cost For the baseload plant retirement to have an effect on the market outcome and the competition in the market, whether/how the distribution of the industry-level marginal costs (merit order) is affected by the retirement is crucial. This section explores how the cost curve changes with the retirement, and how this effect differs by the intensity of the gas price shock which is an input cost shock to the majority of the generation.

To summarize, the effect varies quite significantly by the types of plants retiring and by the presence of the gas price shock. First, when considering only the coal-fired generation, retirement causes a minimal disturbance to the cost curve when the gas prices are low (i.e., gas price shocks are not present), whereas the effect is quite substantial with higher gas prices. In other words, the retirement of coal-fired power plants would affect the industry

long as the mean of costs stays the same.



(a) normal day without the gas price shock: gas price = \$ 4/mmbtu



(b) day with the gas price shock (gas price = \$ 15/mmbtu)

Notes: The graph is generated with the generator-specific marginal costs estimated for the empirical analysis. CF2 refers to a case when the coal power plant of size 1550 MW retires. CF8 refers to a case when all the coal power plants retire.

Figure 3: The effect of the retirements on the marginal cost curve: coal-fired power plants only

cost curve significantly only when accompanied by the gas price shock.

To illustrate this, I plot the original industry marginal cost curve together with the curve after applying the coal plant retirement of size 1,500 MW (CF 2 in the graph), and also after applying all the existing coal plants to retire (CF8 in the graph). I replaced the retired coal and nuclear plants with the hypothetical gas-fired plants of the same capacity.¹⁵ Thus, after

¹⁵While it is possible that the retired plants won't be replaced with the same sized gas-fired plants in reality, this assumption is not too unrealistic for the following reasons. First, from the perspective of a grid operator, it is better to have the new power plant at the site where a major power plant used to operate in order to avoid a major disruption in the line transmission. Thus, it is more likely that the grid operator and regulator may encourage firms to reuse the site than to build a completely new one in other parts of the grid, which is also a cost effective way to construct a new gas-fired power plants. Also, it is convenient for us analysis as we can abstract away from the transmission congestion problem which may cause a problem in the counterfactual

applying the retirements, only the composition of the generation assets at the industry level changes to having more gas-fired generation, while the total market capacity as well as the firm-level capacity are kept the same.¹⁶

Panel (6a) of Figure 3 shows industry cost curves of the normal day without the gas price shock. The retirement does not appear to be significantly changing the marginal cost distribution; the cost curves before and after the retirement are almost the same, especially on the low-demand range, with a small change in some parts of the curve that are not visibly noticeable. This is a result of gas price and coal price being similar when the gas price shock is absent, in which case the marginal cost of generating electricity using coal or gas are similar. In this case, the retirement would not change the distribution of marginal cost curve and the merit order of generation much.

On the other hand, we observe noticeable shifts and rotation in the cost curves after the retirement when gas prices are higher, as shown in Panel (6b) of Figure 3. Under high gas prices, the marginal cost of generating with gas plants become significantly higher than that with coal plant. Thus, replacing coal plants with gas-fired plants shifts the portion of the supply curve that used to be produced by the coal plants. This implies that a replacement that is currently cost efficient could be extremely costly in the future, under certain circumstances. Also, note that the cost curve changes further as the size of the retirement increases.

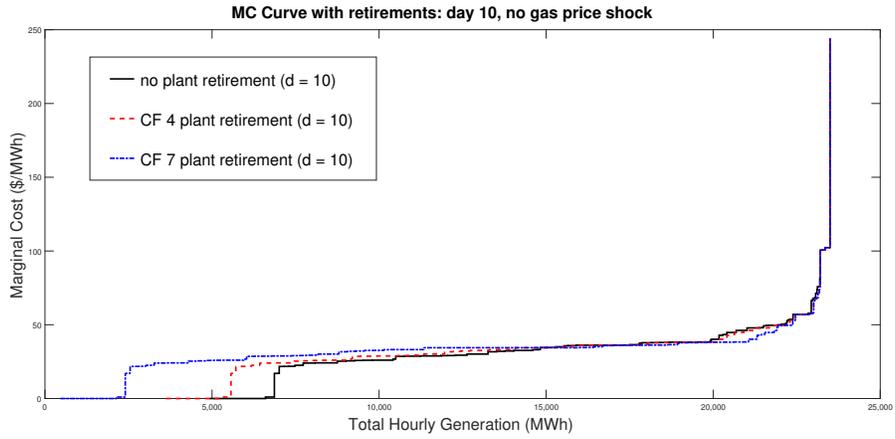
The actual retirement that occurs in the market, however, includes not only coal plants, but also the nuclear plants that have even lower generation cost than the coal plants.¹⁷ The retirement's effect on cost curve will show a different pattern in this case. Figure 5 shows the curves constructed in a same way as in Figure 3, but with different set of retirements applied. There is more shift-ins of the curve due to zero-cost nuclear plants being replaced with gas-fired plants. Thus, we observe some disruption in the curve even when the gas prices are low, especially in the low-demand range. The curves presented here would be closer to what is expected in this market after the planned retirements take place.

What implication does it have on the market competition and outcomes? Overall, the retirement causes a level shift and a change in the slope of the industry marginal cost curve. This implies that the retirement is likely to change the market outcome even absent of competition (i.e., perfectly competitive outcome), at a given demand. Moreover, the change in the slope of the cost curve – resulting from a disruption in the distribution of marginal cost among firms – implies a change in the residual demand curve of strategic firms, in which

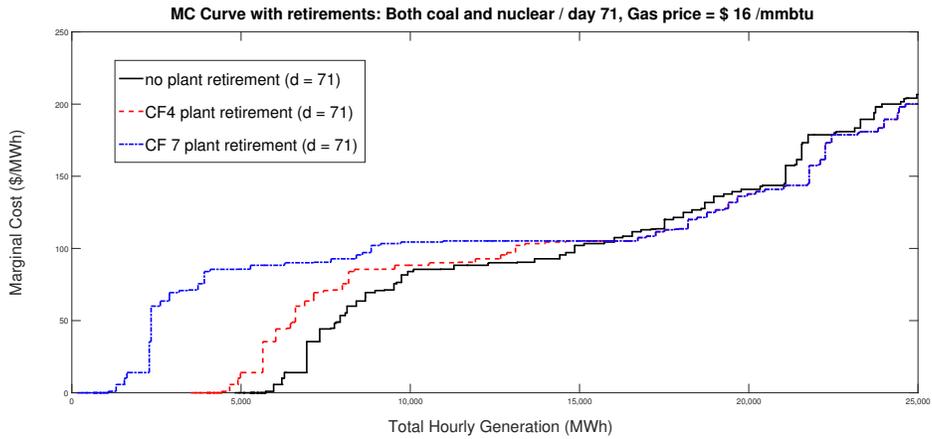
simulation. Indeed, some of the retired coal power plants in New England are converting the site to gas-fired plants. (site the example)

¹⁶I used the average of the estimated marginal cost of gas generators for the marginal costs of these hypothetical gas power plants, which I will elaborate more in the model section

¹⁷While the marginal cost for nuclear plants are not zero when accounting for O&M cost, here I let it to be zero as nuclear plants always submit zero price bids in the market.



(a) normal day without the gas price shock: gas price = \$4/mmmbtu



(b) day with the gas price shock (gas price = \$ 15/mmmbtu)

Notes: The graph is generated with the generator-specific marginal costs estimated for the empirical analysis. CF4 refers to a case when all planned retirements (by 2019) is accounted for, which includes not only coal plant, but also the nuclear power plants. CF7 refers to a case when all the baseload coal and nuclear power plants in this market retires.

Figure 5: The effect of the retirements on the marginal cost curve: coal and nuclear power plants

Counterfactual cases	Total accumulated capacity of retired plants (MW)	Type of plant retirements applied in the counterfactual simulation
(1)	7,400	All of the planned retirements (retires by 2019)◇
(2)	–	All coal-fired plants in the market: coal plants used in case (1) + remaining coal plants
(3)	11,255	All baseload plants (coal + nuclear) in the market

Notes: ◇ includes Salem Harbor, Mt. Tom Station, Vermont Yankee, Brayton Point Station, Pilgrim Nuclear Station.

Table 4: Description of counterfactual plant retirements applied in the simulation

case the competition is likely affected. Since the disruption of cost curve does not occur uniformly across demand levels, the aggregate level of electricity demand which determines where the market clearing prices will be set is important factor. More discussion can be found in the Appendix.

4 Description of the counterfactual situations

Baseload plant retirement As summarized in Table 2, plant retirements occurred not at once, but sporadically over time, starting from mid 2014. Since the retired capacity in each occurrence is too small to have a significant impact on the grid, event study type of analysis will not capture a meaningful effect. Moreover, we do not observe any day in the post-retirement sample that is affected by a significantly large gas price increase. As one of the central focus of the paper is to analyze the effect considering the volatile nature of the gas fuel, an empirical analysis relying exclusively on data is not possible.

Therefore, a counterfactual analysis seems more suitable for analyzing the effect of the plant retirement on market outcomes and competition. I used the actual retirements that occurred or planned as of 2013, which are summarized in Table 2. I aggregated these into groups and applied each group of retirements at once in the counterfactual simulations. Detailed descriptions of the retirement groups are provided in Table 4. Case (1) considers the complete set of soon to be realized retirements, while case (2) and (3) expand the set to all baseload generation including those having no plans to retire yet.

By doing so, we mimic the industry that is likely to emerge in the near future. Note that every other market conditions – such as the number of firms, generation mix of the firms not directly affected by the retirement, price responsiveness of fringe suppliers and the aggregate market demand – are kept the same in the counterfactual.

Accounting for the gas price shock The preliminary analysis of the industry-level marginal costs implies that the impacts of the base load retirement differs by the level of the gas price shock. Therefore, we must conduct counterfactual simulations for different intensities of the gas price shocks. To do so, I selected different days in the sample that vary in the intensity of the gas price shock proxied by the gas price index of the day. Counterfactual retirements are applied to each of the selected days, thus comparing the outcome differences across days would reveal how the retirement's impact differs by the gas price levels. Note that the days selected have similar levels of aggregate demand (used daily average demand and peak demand).

I estimate the marginal costs of the fossil fuel generators separately for each selected days and use the estimates in the counterfactual simulations. These cost estimates, therefore, reflect the changes in marginal cost of gas generators to different levels of gas prices. The estimation of marginal cost utilizes the rich bidding data and the methodologies developed in the empirical auction literature (Reguant, 2014; Kastl, 2012; Hortacsu and McAdams, 2010). I will detail the estimation procedure in the Appendix.

Replacement of retired power plants While the retired plants exit the market without any replacement in the short term, new generating capacity will be added to the grid in the long-term, most of which are natural gas-fired plants.¹⁸ However, there is substantial uncertainty in which firms will add new capacity in the future, or whether the firm that used to operate the retired plant will add new capacity as a replacement.

I consider several different scenarios regarding the replacement of retired plants. Among them, the main setting is where I assume that the retired power plants will be replaced with hypothetical gas-fired power plants of the same capacity as the retired ones. This assumption suits our analysis better as we can eliminate other confounding factors – such as the change in the total industry capacity and firm-specific capacity – that are also known to affect the competition and market outcomes. As the primary focus of this study is on the situation where the industry is more concentrated on generation assets that are more prone to input cost shock, the *complete* replacement assumption controls for other factors and alters only the composition of generation assets.¹⁹

Assuming an installment of a new gas power plant with the capacity equivalent to the retired one is a very strong assumption, but not totally unlikely. Indeed, some coal plant sites are being converted to gas power plants. Also, from a system operator's perspective, it is better to build a new plant on the retired site to avoid transmission congestion problem.

¹⁸EIA, Annual Electric Generator Report, 2018

¹⁹Moreover, I want to avoid analyzing the market impact of an (abrupt) closure of the power plant on market outcomes, which has been studied already in Davis and Hausman (2016). The complete replacement assumption is necessary for at least isolating the effect coming from the short-term shift-in effect from the effect resulting from an increased concentration.

Nevertheless, I will consider other scenarios regarding the installment of new capacities in the additional counterfactual analysis. For instance, the new power plants may be constructed by small entrants (fringe suppliers).

Since we do not have any information on the efficiency and marginal cost of the *hypothetical* gas power plants, I approximated their marginal costs using the average heat rate (efficiency) of the most recently constructed gas power plants, as well as the data on gas price index and emissions costs.²⁰

Accounting for the equilibrium model: horizontal structures To compute the equilibrium under counterfactual situations, we need a model that describes decision makings of firms. Since firms in the wholesale electricity market compete for production in the auction, the supply function equilibrium (SFE) model best describes their behavior.

However, computation of counterfactual supply function equilibrium is challenging due to a well-known multiple equilibria problem (Klemperer and Meyer, 1989). Also, the optimal bidding model in the multi-unit uniform auction, which relies on necessary condition of optimization, does not describe the structural bidding decisions of firms.²¹ In many cases, the counterfactual analysis in the wholesale electricity market setting relies on simulating the Cournot equilibrium (Bushnell, Mansur and Saravia, 2008; Ryan, 2014; Ito and Reguant, 2016), utilizing the findings of Klemperer and Meyer (1989) that multiple supply function equilibria (SFE) are bounded by the perfectly competitive equilibrium and the Cournot equilibrium. Therefore, the competitive and Cournot equilibria simulated under counterfactual situations, in principle, become lower and upper bounds of the market outcomes we expect to see in the actual counterfactual supply function equilibrium. The methodology adopted in this paper is closest to that used in Borenstein et. al (1999) and Bushnell et.al. (2008), where I simulate counterfactual outcomes for both competitive and Cournot equilibrium.²²

Besides providing a bound for our possible counterfactual SFE, comparing the outcomes simulated under different horizontal market structures reveals the role of strategic interaction in determining the market outcomes. Cournot model incorporates strategic interaction between firms (strategic players) and thus gives indication of how the competition changes under counterfactual situations. On the other hand, the perfectly competitive market outcome does not account for strategic interactions, thus only reveals the outcome change resulting from the change in the merit order (industry marginal cost shift). For example,

²⁰The average heat rate of new gas power plants that started production in 2014 was taken from EIA's report. Marginal cost is represented as the heat rate multiplied by the sum of the gas price and the emission price.

²¹However, multiple equilibria problem does not pose any challenge to *estimation* of model parameters that use necessary condition of optimization at the observed equilibrium.

²²However, limitation exists in this type of bound analysis. Even if we show that the bound itself increases in counterfactual situations it does not necessarily indicate that our outcomes under SFE increase compared to the pre-counterfactual situation, except for some cases when competitive outcome under counterfactual exceeds that of the observed SFE.

Before	Plant retirement	After
(B2) Cournot equilibrium	→	(A2) Cournot equilibrium
Observed equilibrium (SFE)		
(B1) Competitive equilibrium	→	(A1) Competitive equilibrium

Table 5: Description of the counterfactual cases to be simulated

when a firm produces 100 MWh under competitive model but produces only 50 MWh under Cournot model, given the same demand, then such a difference is coming from the strategic consideration, possibly firms withholding quantity to exercise market power. Therefore, the outcome difference between two different market structures can be attributed to the competition.

In order to assess how the retirement affects the competition, we can compare the change in market outcomes before and after applying the counterfactual retirement, *across* different market structures. In other words, how differently outcomes respond to the retirement when allowing for strategic interaction and not – $(B2 - B1)$ vs. $(A2 - A1)$ according to Table 5 – reveals the retirement’s effect on competition (and market power). The change in market outcomes under the competitive model (i.e., $A1 - B1$) captures the natural response in firm-level quantities that arise from the retirement-induced disruption in the industry-level cost distribution (industry-level marginal costs). Such natural response in quantities are controlled in order to capture the pure part of the quantity response related to the motives for strategic withholding.

5 Description of Model and Data

It is straightforward to compute the perfectly competitive market equilibrium; firms produce electricity as long as the marginal cost of production is less than or equal to the market price, and the market clearing price is determined at the intersection of aggregate supply and demand for electricity. To compute Cournot equilibrium outcomes, general formulation of how strategic firms compete according to the Cournot assumption is necessary. I adopt the Cournot model used in Bushnell, Mansur and Saravia (2008) to compute counterfactual Cournot outcomes. In the subsequent sections, I describe the model and several assumptions imposed when applying the data to the model.

5.1 Model Description

5.1.1 Residual Demand Curve

Residual demand is the demand faced by N_{st} strategic firms together. Strategic firms are chosen among those operating several generators and with a large capacity in total (e.g. at least 500 MW). More details of the selection of strategic firms will be provided in the following section. The residual demand, $Q_{s,t}$, must equal the aggregate electricity demand (\bar{D}_t) less the electricity generated by non-strategic fringe suppliers together ($Q_{ns,t}$), which is shown below. Subscripts s and ns denote strategic and non-strategic, respectively.

$$Q_{s,t} = \bar{D}_t - Q_{ns,t}(p_t)$$

Because the demand side of the wholesale electricity market – local distribution companies – has obligations to supply electricity to residential customers, they tend to submit price insensitive bids which make the aggregate demand (\bar{D}_t) to be almost perfectly inelastic. However, the residual demand faced by strategic firms is elastic because the quantity supplied by non-strategic firms who behave as price takers is responsive to the market price.²³

We need a (smooth) demand function to clear the market within the model.²⁴ I adopt a simple log-linear demand specification used in Bushnell et. al (2008). Functional form of a residual demand curve is specified as follows:

$$Q_{s,t} = \alpha - \beta \ln(p_t) \Leftrightarrow p_t = \exp((\alpha - Q_{s,t})/\beta) \quad (1)$$

Parameter α and β must be estimated before we run counterfactuals. The intercept of the residual demand, α , is calculated from the price and strategic quantity of the observed equilibrium. That is, exploiting the fact that the actual price and quantity pair – $(P_t, Q_{s,t})$ where $Q_{s,t} = \sum_{i=1}^{N_{st}} q_{it}$ – is a point on the residual demand curve of day t , the intercept α can be obtained by plugging this into the specified demand curve.

Estimating the slope of a residual demand An important part is to estimate the slope of the residual demand curve, β . While BMS (2008) estimates a single parameter for the entire sample, I estimate β separately for each (t, h) observation, similarly as in Ito and Reguant (2016). This is because the changing levels of gas prices in our sample lead to different responsiveness of fringe supply across sample days. For instance, when gas prices are low

²³The New England electricity market usually imports or exports wholesale electricity from the Canadian electricity market and the New York electricity market (ISO-NY). It mainly imports from Canada, while imports and exports to the New York market depending on the daily market and transmission conditions.

²⁴Although we have complete data on demand side bids which can be used to construct demand curve, it is better to have a more general and smoother demand function. Also, because I model firms to compete in quantity, it is difficult to obtain market clearing price without a general form of market demand function.

so that the dispersion in costs of generators across different fuel types are not salient, price bids of fringe suppliers are close to each other. In this case, a small price increase could result in a large quantity increase by the fringe suppliers, in other words, responsive fringe supply. On the other hand, when gas prices are high, the increased dispersion in the costs and price bids of generators make the fringe supply to be sparsely located along the supply curve, thereby having a lesser sensitivity of fringe supply to a small price increase.

Thus, for a more precise analysis, I estimate $\beta_{t,h}$ for each day using the bidding data. With the observed price and quantity bids ($\langle p_{ijth}, q_{ijth} \rangle$) of non-strategic firms, the residual demand curve is constructed non-parametrically, which allows estimation of the slope β_{th} . Since we are dealing with the possibility of having non-local simulation outcomes, I specify the residual demand curve to be a piecewise linear function, and estimated slopes using the spline method with two knots. The slope estimated from the pre-retirement sample can be used for counterfactual cases (where the retirement of plant is applied) because all the firms operating the retired plant are included as part of strategic firms.²⁵

5.1.2 Firm's problem

For each strategic firm $i \in \{1, \dots, N_{st}\}$ and for time $t \in \{1, \dots, T\}$, firm i choose to produce electricity q_{it} that maximizes profits:

$$\begin{aligned} \max_{q_{it}} \pi_{i,t}(q_{it}, q_{-it}) &= p_t(q_{it}, q_{-it}) [q_{it} - q_{it}^f] + p_{it}^f(q_{it}^f, q_{-it}^f) q_{it}^f - C(q_{it}) \quad \text{for } \forall i \quad (2) \\ \text{s.t. } q_{it} &\geq 0 \quad \text{and} \quad q_{it} \leq q_{i,max} \end{aligned}$$

Electricity producing firms tend to forward contract a certain amount of their generation with the demand side, shown as q_{it}^f at a pre determined price, shown as p_{it}^f . They mutually agree to buy and sell the contracted amount at a forward price, before the actual production takes place. For this reason, the forwarded quantity and forward price are assumed to be exogenous at the time of the firm's production decision, thus do not affect strategic decisions of firms regarding the quantity produced, q_{it} .²⁶

²⁵We have omitted import and export bids when calculating the slope of the residual demand curve. Omitting these bids won't critically affect our slope estimates much first because the size of the import quantity is not sensitive to the price in the New England market. That is, very little variation exists within a day for the imported quantity, while the prices vary quite largely across hours. Also, daily variation in import size is very small, almost always importing a fixed amount of electricity, which may be the point where the transmission constraint is binding. All of these indicates that import size is more binded by the daily transmission condition and capacity, and not much by the price. Import from Canada, which constitutes a majority of the imported electricity, flows in irrespective of price, limited by the capacity of transmission lines from Canada to New England. Secondly, omitting export quantity will not affect our estimates much because exported amount of electricity is very small compared to import.

²⁶ p_f disappears from the first order condition in the process of differentiating profit with respect to q_{it} .

5.1.3 Cost Functions

We need a firm-specific cost function because firms in the model optimally decide on single q_{it} . If a firm operates total J number of generating units, we can construct a cost curve $C(q_{it})$ of firm i by arranging the marginal cost values of these units from smallest to higher value. Then, the marginal cost is represented as below:

$$C'(q_{it}) = mc_j \quad \text{if} \quad q_{it} \in \left(\sum_{k=1}^{j-1} q_{ik}, \sum_{k=1}^j q_{ik} \right) \quad (3)$$

I assume the cost curve of each generator to be linear so that the marginal cost of each generator is constant over quantity, i.e. scalar value. Linear cost assumption is common in the literature (Bushnell, Mansur, and Saravia, 2008; Ito and Reguant, 2016; Ryan, 2017) and many others have made this assumption in their analysis. This assumption allows us to specify the firm-level marginal cost to be piecewise linear, which is again a functional form commonly used in the electricity market studies (BMS, 2008; Ito and Reguant, 2016, for example).²⁷ The unit specific marginal cost, mc_{ij} , which I estimated from the bids data, together with unit capacity and generation data are used to construct the cost curves.

5.1.4 Cournot Equilibrium Outcomes

Cournot equilibrium is represented as a set of quantities, $\mathbf{q}_t^* = [q_{1t}^*, \dots, q_{Nt}^*]$, that simultaneously satisfy the system of first order conditions. The first order conditions of strategic firms are shown below:

$$\mathcal{L} \equiv \pi_{it} + \lambda_{it}(q_{i,max} - q_{it}) \quad \forall i \in \mathcal{F}_s \quad (4)$$

$$\frac{\partial \mathcal{L}}{\partial q_{it}} = \frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \leq 0, \quad q_{it} \geq 0, \quad \frac{\partial \mathcal{L}}{\partial q_{it}} q_{it} = 0 \quad (5)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_{it}} = q_{i,max} - q_{it} \geq 0, \quad \lambda_{it} \geq 0, \quad \frac{\partial \mathcal{L}}{\partial \lambda_{it}} \lambda_{it} = 0 \quad (6)$$

²⁷As mentioned in Reguant (2014), generators can have a non-linear component in their cost curve, in which case the marginal cost would increase with quantity. Omitting the non-linear component would be problematic for coal plants, but not a critical problem as many of the coal plants in our study are being excluded in counterfactual simulations. Later, I will add a non-linear component to the cost to further complement the analysis.

We can rewrite equations (5) and (6) by plugging in the actual specifications, which are shown below in equations (5a) and (6a):

$$\frac{\partial p_t}{\partial q_{it}} [q_{it} - q_{it}^f] + p_t - C'(q_{it}) - \lambda_{it} \leq 0, \quad q_{it} \geq 0, \quad \frac{\partial p_t}{\partial q_{it}} [q_{it} - q_{it}^f] + p_t - C'(q_{it}) - \lambda_{it} q_{it} = 0 \quad (5a)$$

$$q_{i,max} - q_{it} \geq 0, \quad \lambda_{it} \geq 0 \quad (q_{i,max} - q_{it}) \lambda_{it} = 0 \quad (6a)$$

Nonstrategic, fringe suppliers are assumed to be price takers. First order conditions of non-strategic fringe suppliers are shown below:

$$p_t - C'(q_{it}) - \lambda_{it} \leq 0, \quad q_{it} \geq 0, \quad (p_t - C'(q_{it}) - \lambda_{it}) q_{it} = 0 \quad (7)$$

$$q_{i,max} - q_{it} \geq 0, \quad \lambda_{it} \geq 0 \quad (q_{i,max} - q_{it}) \lambda_{it} = 0 \quad (8)$$

Derived conditions become a standard (non-linear) mixed complementarity problem (MCP). Now we can summarize the above conditions using complementarity symbols:

$$\begin{aligned} \frac{\partial p_t}{\partial q_{it}} [q_{it} - q_{it}^f] + p_t - C'(q_{it}) - \lambda_{it} \leq 0 \quad \perp \quad q_{it} \geq 0 & \quad \forall i \in \mathcal{F}_s \\ p_t - C'(q_{it}) - \lambda_{it} \leq 0 \quad \perp \quad q_{it} \geq 0 & \quad \forall i \in \mathcal{F}_{ns} \\ q_{i,max} - q_{it} \geq 0 \quad \perp \quad \lambda_{it} \geq 0 & \quad \forall i \end{aligned} \quad (9)$$

These complementarity conditions are similar to the ones derived in Bushnell, Mansur, and Saravia (2008). We can also convert the system to a new form (similar as the one depicted in Ryan (2014)) by removing multiplier λ_{it} from the equations,

For $\forall i \in \mathcal{F}$

$$\begin{aligned} 0 < q_{it} < q_{i,max} & \Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} = 0 \\ q_{it} = 0 & \Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} \leq 0 \\ q_{it} = q_{i,max} & \Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} \geq 0 \end{aligned} \quad (10)$$

where the derivative of profit, $\frac{\partial \pi_{it}}{\partial q_{it}}$, of strategic and nonstrategic firms take different forms. Details can be found in the Appendix.

The Cournot equilibrium quantities of production, $\mathbf{q}_t^* = [q_{1t}^*, \dots, q_{Nt}^*]$, is the \mathbf{q}_t that si-

multaneously solve the above system of complementarity conditions. To obtain the solution of this problem, I use PATH algorithm which is effective in solving mixed complementarity problem (Kolstad and Mathiesen, 1991; Dirkse and Ferris, 1998).

5.2 Data

Data on firm-level quantity and maximum capacity comes from bidding data and Seasonal Claimed Capacity data available from the ISO-New England website. Electricity generating firms in the wholesale electricity market must sell electricity in a daily auction which consists of total 24 hourly auctions. A typical bid submitted by a firm for each of its generating unit consists of price and quantity pairs, $\langle p_{ijht}, q_{ijht} \rangle$, and the firm-level quantity q_{iht} of hour h of day t can be measured by adding up the unit-level quantity bids. Demand is constructed with the demand bids submitted by the local distribution companies. The net imported amount of electricity is taken from ISO-NE's report on the final net interchange (net import). The market (auction) clearing prices are taken from the ISO-New England website. I use energy component price, a single price that clears the entire system before accounting for the local congestion costs. Because I cannot account for the complicated process of determining transmission congestion costs when clearing the market in my model, I use energy component price as a reference price level throughout my analysis.

As mentioned in the previous section, I use *estimates* of marginal costs instead of measuring them. There are broadly two ways of obtaining marginal costs of (thermal) electricity generators in the literature. Most common approach is to measure the marginal costs using data on fuel price and heat rate (efficiency) of generators. Another approach is to estimate the marginal costs that rationalize the bids that firms submit in the electricity auctions. Although the latter approach involves additional modeling of optimal bidding decision of firms and requires additional computation, it suits better to obtain the real opportunity costs of firms especially when the market experiences input cost shocks. Because an important element of my study is to understand how market outcomes and firm behavior changes under cost shocks, I rely on the second approach and use the *estimated* marginal costs. Details of the bidding model and the estimation procedure are elaborated in Kim (2018). However, marginal cost estimates cannot be obtained for some small fringe generators, hydroelectric plants and base load generators that usually bid zero price bids – such as the nuclear plants – because the optimal bidding model can get estimates for units that are close to being marginal. These units are far away from the market clearing price, thus have no chance of becoming the marginal unit. I use the price bid of these units as a measure of marginal costs because firms will submit a bid that equals the marginal cost for its unit having no chance of being marginal.

Finally, we need information on the forward contracted amount of electricity, represented

(A) Summary statistics of β_{th}					
mean	4.19	min	2.52	max	7.87
(B) Regression of β_{th}					
log (Demand):	0.42	log(gprice):	-0.19	log ($Q_{st,obs}$):	-0.51
	(0.06)		(0.02)		(0.03)

Notes: N = 233. Standard errors in the parenthesis. log(gprice) is logged value of spot gas price index. (B) regression section reports the estimate of OLS of the β_{th} on the variables listed in the row. Unit of β_{th} Demand, and strategic quantity is GWh. Unit of daily gas price is \$/mmbtu.

Table 6: Summary and some basic regression result of residual demand slope β_{th}

by q_{it}^f in our model. Unfortunately, data does not exist for the contract position as it is determined through confidential bilateral negotiations between electricity generating firms and the demand side. The optimal bidding model used to estimate the marginal cost enables estimation of the forward contract parameters as well. I use the forward contract rate parameter (represented as a % of the firm's daily electricity generation) estimated in Kim (2018) and multiply the rate with the actual quantity produced by the firm to generate the forward contracted amount of quantity, q_{it}^f .

6 Results

6.1 Residual Demand Slope Estimates

The estimated slope parameter is summarized in Panel (A) of Table 6; the average is around 4.19 GW with some variation across sample days. To explore how the slope varies by demand and gas price levels, I run a simple regression where the estimated slopes β_{th} are regressed on daily demand (log(Demand)) and gas prices (log(gprice)), shown in Panel (B). Note that I have also controlled for the strategic quantity ($Q_{st,obs}$) because the slope of a residual demand is systematically larger when smaller number of firms are grouped into strategic firms (confirmed by the negative coefficient estimates).

The estimates of log (Demand) and log(gprice) suggest that the slope is larger when the daily market demand is higher, and the slope is smaller when the daily gas price is higher. How can we rationalize this finding? First, note that the majority of non-strategic supply comes from the gas-fired generators, most of them having relatively higher cost of generation among the entire generation pool as well as among gas generators. Thus, the non-strategic supply is less price responsive in low demand hours when prices are low, but becomes more responsive as we approach the higher end of the industry supply curve where

	Total	Competitive Price			
		Low Demand (D1)	⇒ (D2)	High Demand (D3)	(D4)
Before	84.2	74.4	81.4	83.1	100.3
After	83.7	78.4	81.6	81.7	94.1
Further Controlling for the Daily Gas Prices					
(A) Low Gas Price					
Before	59.1	51.5	54.0	53.6	74.8
After	57.2	51.8	53.7	52.7	68.6
(B) Med Gas Price					
Before	86.7	77.4	80.1	85.6	112.3
After	85.8	81.7	77.8	83.1	104.4
(C) High Gas Price					
Before	134.9	116.6	132.6	148.4	152.1
After	138.0	127.5	135.7	148.0	147.9

Notes: This is the result based on November 2018 simulation (file 5 mat. retired). D1 is demand below 14 GW, (D2) is between 14 and 15.5 GW, (D3) is between 15.5 and 17 GW and (D4) is above 17 GW. The frequency of observation of each demand bins are roughly the same. The cut off values for the gas price are: (A) low gas price is gas prices between 4 to 9, and (B) medium is between 9 and 15 and (C) is above 15 up to 27. Cut off values for each gas price bins are determined after examining the pattern of price changes of competitive prices. Average values of simulated competitive prices are reported in the Table. For more summary statistics, check the complete Table provided in the Appendix. Outliers dropped.

Table 7: Counterfactual Competitive Price Simulation Result

most of the gas generators are located. Moreover, non-strategic, fringe suppliers are more densely populated when the gas price is low, making the residual demand more price responsive, whereas fringe suppliers are more sparsely located with higher gas price, thereby having a smaller slope in this case.²⁸

6.2 Competitive equilibrium outcomes

We first simulate the market price and the firm-level quantity under the counterfactual *competitive* equilibrium. In competitive equilibrium, each firm starts supplying electricity from their lowest cost generators; they supply the quantity that minimizes the cost of production given the total market demand which is fixed to the level observed in the data.

²⁸This could also be a result of having increased dispersion in the marginal cost of generation when the gas prices are higher. A large gas price shock makes more dual generators to switch fuels, and firm-specific gas prices to vary quite substantially even within a day. For more discussion of this issue, see Kim (2018).

Therefore, the productive efficiency will be achieved in competitive equilibrium as the production always starts from the lowest-cost to the higher-cost generators at the industry-level.

I group demand into four different bins (D1 to D4) and gas prices into three different bins (A to C), and report the average within each bin. It is common in electricity market studies to analyze the result separately by *peak* and *off-peak* hours. Here, (D1) and (D2) roughly correspond to the off-peak hour demand levels, and (D3) and (D4) to those of peak hours.²⁹

Table 7 shows the result. Overall, we find considerable change in the competitive price after the retirement, indicative of a significant disruption in the marginal cost distribution and the merit order of dispatch among generators. The results in first two rows of the table show that the competitive price increases the most in the low-demand sample (D1), and decreases the most in the high-demand sample (D4). This indicates that the retirement could lower the price during the peak hours, at least for the competitive prices.

However, this hides heterogeneity in price changes with respect to the gas price variation. Panels (A) to (C) present the average taken within each “demand-gas price” bins, accounting for different gas prices across the sample. When gas prices are low (panel (A)), the gas generation is economically comparable to or even cheaper than the coal generation. In this case, the competitive price does not change much or even decreases on average after the retirement, especially when the demand is higher. On the other hand, with higher gas prices – shown in panels (B) and (C) – the retirement results in replacing low-cost generation with higher cost generation, thereby leading to a rise in competitive prices in low demand range (D1) where the baseload plants take a large part of the generation.

One takeaway is that the competitive prices will drop quite significantly after retirement in high-demand hours, the demand range where the price increase is most concerned. Thus, if the market performs close to perfect competition, there would be some benefits from the industry transformation.

6.3 Selection of Strategic Firms

Competitive equilibrium and the observed equilibrium Since we simulate the market price and the firm-specific quantity under the counterfactual *competitive* equilibrium, we can measure the extent to which the actual market outcome of the observed days in our sample (one of SFE) departs from the competitive benchmark. This is useful for selecting firms that are observed to behave strategically in the actual equilibrium. While it is common and more convenient to assume that large-scaled firms are strategic players, I further restrict the set of strategic players among large-scaled dominant firms through such comparison. Even a

²⁹In a typical market, absent of gas price shock or any disruption, the off-peak hours are when market power is exercised less, whereas the peak hours are when the market power is most likely to be present (Borenstein and Bushnell, 1999; Borenstein, Bushnell and Wolak, 2002).

large-scaled firm can behave quite competitively depending on market conditions (e.g., level of market demand), thus treating these firms as strategic players in our Cournot simulation could exaggerate the strategic outcome. Besides, this exercise can also provide insight into the extent of market power of the observed (SFE) equilibrium.

Strategic firms used in counterfactual simulation Firms that are capable of behaving strategically will withhold their production compared to the competitive level in order to profitably raise the market price. I have selected firms whose quantity observed from the data departs significantly from the quantity simulated under competitive model.³⁰ I term these firms as strategic firms and allow them to behave strategically in the Cournot model simulation, while the rest of the firms are grouped as non-strategic firms, i.e., fringe suppliers, that behave as price takers.³¹

Using these selected firms as strategic players in the Cournot simulation yields market outcomes that are closer to the observed SFE outcomes. I find that selecting strategic firms in an ad-hoc way – for example, by taking a few large-scaled firms – could result in outcomes that depart quite substantially from the observed equilibrium, even considering that Cournot equilibrium is an upper bound of the SFE. An ad-hoc selection of firms may be treating non-strategic firms not capable of withholding quantity to do to so, thereby ending up producing too little in the simulation. Showing the resemblance of the simulated Cournot outcomes of the pre-retirement sample to the observed equilibrium outcome gives validation to the use of Cournot model to simulate counterfactuals in this market setting.³²

Table 8 summarizes the capacity of strategic firms over the entire sample which totals 23 firms (19 if restricting only those not exiting the market). While the total number of firms is large, maximum 14 firms are considered strategic in each (d,h) market used in the simulation. All of these selected firms own considerably large capacity assets as shown in the table. Table also presents information of strategic firms that own the retired power plant, as well as those operating base load generation considered to be at risk of retirement.

More detailed analysis of strategic firms' observed production, compared to the competitive benchmark, is provided in Appendix A.3.

³⁰Quantity difference must be at least 10 percent of the competitive quantity

³¹Our categorization of fringe supplier here departs from a conventional definition of fringe suppliers – a firm operating only a single, small-scale power plant – as the fringe supplier may operate more than one power plants and generators. Finally, I used the observed bids of fringe suppliers when estimating the residual demand faced by strategic firms together.

³²Note that it is okay to expand the set of strategic firms beyond the selected set in the simulation considering completely different counterfactual situation – e.g., the industry after plant retirements are completed – because the goal of the simulation is not to mimic the equilibrium observed in the data as closely as possible.

	Capacity (MW)				
	N	minimum	median	maximum	total sum
Strategic firms	19	207	860	4,753	23,078
Firms owning retired plants	5	587	1,561	2,657	7,404
Firms owning plants at risk of retirement	4	509	970	1,385	3,835
Capacity of five largest firms	firm 33	firm 28	firm 37	firm 71	firm 61
	4,753	2,657	1,987	1,891	1,561

Notes: This table summarizes the capacity of the strategic firms detected based on their observed production responses in comparison to the counterfactual competitive production. The capacity reports the total capacity of a firm, not the capacity of the retired power plants of the firm. Firms owning retired plants are those that have already announced retirement of their baseload plants as of 2018 and those at risk are firms that operate base load generation but have not announced retirement so far. Total number of firms in this industry is 86. Since the actual identities of the firm are undisclosed in the main data set, I list the five largest firms by their anonymous firm ID.

Table 8: Summary of Capacity of Strategic Firms

6.4 Strategic Equilibrium Result

Before discussing the result, it is useful to provide a comparison of our simulated Cournot counterfactual prices to the actual market prices. [provide a bar graph or a line graph].

Table 9 reports the simulated Cournot prices using the selected strategic firms. It appears that Strategic price increases the most in low-demand (off-peak) hours (D1), regardless of the size of the gas price. On the other hand, the impact on high-demand (peak) hours is small, increasing by only 0.3\$/MWh, on average, as shown in (D4). When examining price changes by the size of the gas prices, the electricity price increases more, on average, when the market is under influence of a large gas price shock. For instance, in the column termed “Total”, the price increases by about \$ 5 in the low gas price sample (panel A) but increases by almost \$20 in high gas price sample (panel C). However, note again that the price change reported here, simulated from the Cournot model, is the upper bound of the likely price in the counterfactual situation.

Measuring the unilateral market power However, simply comparing the strategic prices before and after the retirement could be misleading as the disruption in the cost distribution caused by the retirement changes the competitive prices as well. As shown in Table 7, the cost disturbance and the merit order change results in a “natural ” response in the *competitive* price which does not involve any strategic consideration. Therefore, in order to assess the change in the extent of market power, a better measure is how much the strategic quantity (or price) differs from the competitive benchmark, since the presence of a market power results in quantity and price distortion *relative* to the competitive level.

	Strategic Price				
	Total	Low Demand (D1)	⇒ (D2)	High Demand (D3)	(D4)
Before	90.4	76.8	87.2	88.3	112.8
After	99.1	91.0	98.5	95.5	113.1
Further Controlling for the Daily Gas Prices					
(A) Low Gas Price					
Before	62.2	52.4	56.7	56.0	80.9
After	67.9	61.2	65.2	58.8	82.6
(B) Med Gas Price					
Before	94.9	82.4	84.5	92.4	132.0
After	100.2	94.5	87.5	96.3	127.7
(C) High Gas Price					
Before	145.4	117.8	145.3	156.3	173.4
After	165.0	146.7	167.3	181.6	174.8

Notes: This is the result based on November 2018 simulation (file 5 mat. retired). D1 is demand below 14 GW, (D2) is between 14 and 15.5 GW, (D3) is between 15.5 and 17 GW and (D4) is above 17 GW. The frequency of observation of each demand bins are roughly the same. The cut off values for the gas price are: (A) low gas price is gas prices between 4 to 9, and (B) medium is between 9 and 15 and (C) is above 15 up to 27. Cut off values for each gas price bins are determined after examining the pattern of price changes of competitive prices. Average values of simulated Cournot prices are reported in the Table. For more summary statistics, check the complete Table provided in the Appendix. Outliers dropped.

Table 9: Counterfactual Cournot Price Simulation Result

Based on this idea, I compute a measure of market power by comparing the simulated strategic prices versus the competitive prices when firms behave as price takers. For each day and hour market (d,h) in our sample, we can measure the following markup at the market level (represented as a percentage difference):

$$\Delta P_T = \text{markup}_{m,T} = P_{\text{strategic},T} - P_{\text{com},T}$$

where, m denotes the market-level markup measure and T shows whether the sample is pre- ($T = 0$) or post- retirement ($T = 1$). As we are interested in measuring the change in market power caused by the retirement-induced industry transformation, the following double difference of ΔP would represent such change:

$$\Delta\Delta P = \Delta P_1 - \Delta P_0 = \text{markup}_{m,1} - \text{markup}_{m,0}$$

$\Delta\Delta P = \Delta P_{af} - \Delta P_{bf}$						
		Low Demand		\Rightarrow	High Demand	
	Total	(D1)	(D2)	(D3)	(D4)	
$\Delta\Delta P$	13.3	16.0	16.3	7.7	10.7	

Further Controlling for the Daily Gas Prices

(A) Low Gas Price

$\Delta\Delta P$	9.5	10.9	13.2	2.5	8.7
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(B) Med Gas Price

$\Delta\Delta P$	14.9	14.4	10.4	11.3	22.4
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(C) High Gas Price

$\Delta\Delta P$	18.5	25.0	26.0	12.7	6.8
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Notes: This is the result based on November 2018 simulation (file 5 mat. retired). D1 is demand below 14 GW, (D2) is between 14 and 15.5 GW, (D3) is between 15.5 and 17 GW and (D4) is above 17 GW. The frequency of observation of each demand bins are roughly the same. The cut off values for the gas price are: (A) low gas price is gas prices between 4 to 9, and (B) medium is between 9 and 15 and (C) is above 15 up to 27. Cut off values for each gas price bins are determined after examining the pattern of price changes of competitive prices. Average values of simulated price difference are reported in the Table.

Table 10: Price difference, $\Delta\Delta P$

$\Delta\Delta P$ measures the change in the unilateral market power (degree of competition) resulting solely from the retirement – as we are keeping everything else the same in our simulation. The difference is mainly driven by the change in the strategic behavior of the (selected) strategic firms, since the rest of the non-strategic (fringe) firms are assumed to behave competitively in both ($T = 0, 1$) situations.

Note that the average ΔP is 6.2 % during the period before the retirement ($T = 0$) and 17.7 % for the after retirement period ($T = 1$).

Table 10 reports the estimated $\Delta\Delta P$ measure across different demand and gas price levels. The positive $\Delta\Delta P$ indicates an increase in the degree of overall market power after the retirement. Overall, the market power increases further by 13.3. However, the extent of the increase varies by demand and intensity of the shock. The market power increase is most salient during low-demand (off-peak) hours. On the other hand, high-demand (peak) hours experience lesser degree of market power increase. While we have shown that the simulated Cournot prices do not increase much or slightly decrease in (D4) as reported in Table 9, this is offset by the fact that competitive prices also decreased in this demand range, thus the market power measured relative to competitive benchmark still increases after the retirement, shown by the positive $\Delta\Delta P$ value of average 10.

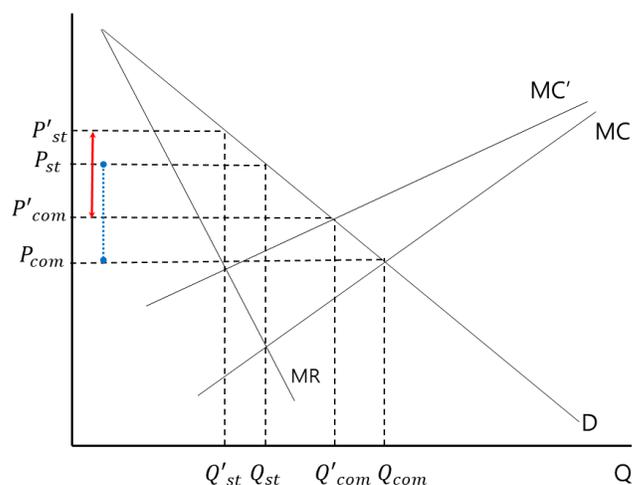


Figure 7: $\Delta\Delta P$ change graphical illustration

However, note that our result is an upper bound of market power change that is likely to happen due to retirement, since the actual strategic behavior can depart from what is predicted from the Cournot model. Despite this, we can learn the changing strategic incentives and likely strategic responses from firms and market outcomes from this result.

6.5 Exploring the source of market power

Given that our results indicate a change in strategic environment as well as the resulting market power after the industry transformation, it is important to examine at the micro-level what factors are important for understanding the result. That is, while the impact on unilateral market power varies with aggregate demand and intensity of gas price shocks, it is more reasonable to think that some factors (other market variables) associated with demand and gas price shocks are affecting the strategic incentives of firms and the market impact of the retirement. Therefore, to investigate the source of the increase in market power, we investigate further into other market variables and strategic behavior at the firm level, exploring the heterogeneity among firms.

We find that market power (the extent of quantity distortion) varies with the demand and gas price levels. This is perhaps due to some market variables that changes along with demand and gas price levels. Three clear patterns arise from our findings; that (i) the retirement has less effect on the market power during peak demand (high demand, D4), (ii) low demand (off-peak) hours suffer the most from the retirement, and that (iii) the effect could be more pronounced when the gas prices are higher. What could be changing with the demand, gas price shock, and with the retirement that leads to this finding?

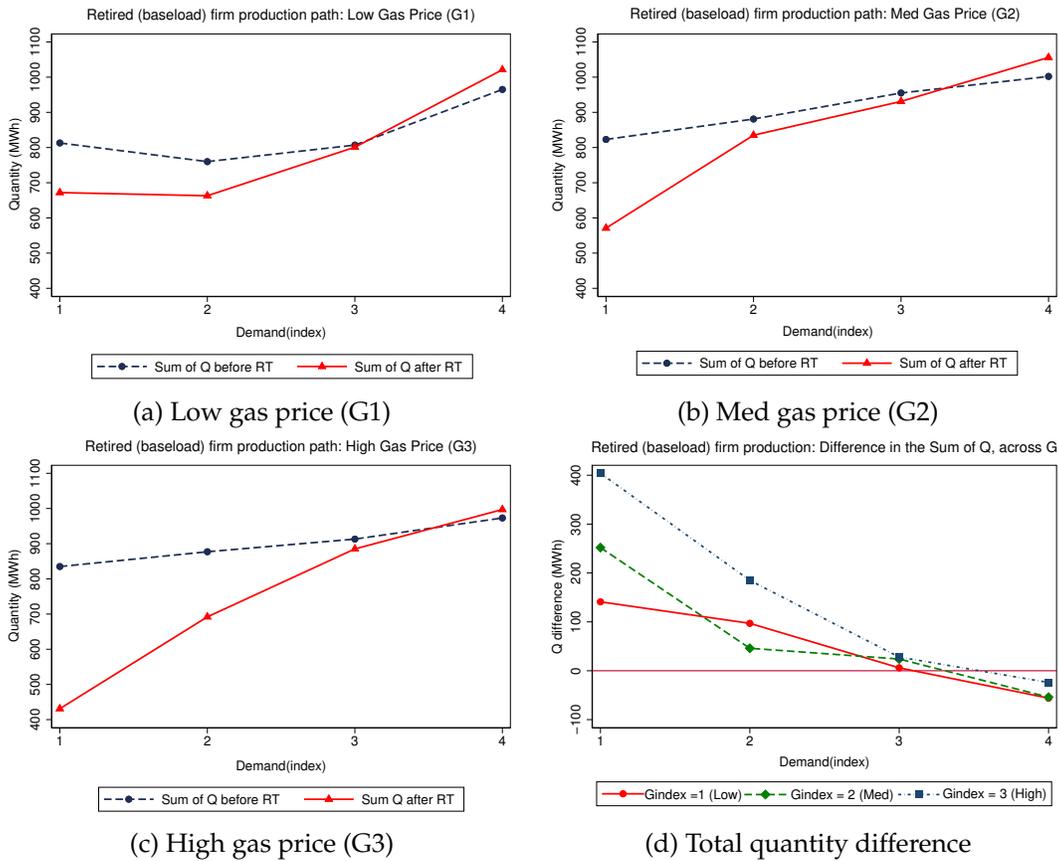


Figure 8: Retired firm production (average) path before vs. after the retirement

How does the retired firms' production change? Figure 8 shows how the average of the total quantity produced by retired firms (firms operating baseload power plants that retire in the counterfactual) together changes after their baseload plants retire and are replaced with gas-fired generators. Average of firm productions is taken within each demand bin (D1- D4), and plotted separately by different intensity of the gas price shock (gas price levels), shown in panels (a), (b), and (c), respectively. Panel (d) summarizes the change (difference between two lines presented in panels (a) to (c)).

After being replaced by gas-fired generators, the production decreases compared to that produced by base-loads before. Not surprisingly, the most stark difference in production occurs in low demand hours (D1 and D2), where the quantity produced by drops most significantly, and drops further as the gas price increases. As the difference in the generation cost between the conventional baseloads and the gas-fired generators becomes larger with a higher gas price, the retirement of these low-cost baseload plants results in increasingly more amount of generation being shifted away from these firms with higher gas prices. The reduced production will be reallocated to other low-cost plants, whose cost is not compara-

bly lower than the retired baseloads. This may cause some additional underproduction by strategic firms, thereby leading to a price increase.

Also note that the pre-retirement production by the conventional baseload generators (retired firms) were not sensitive to the intensity of the gas price shocks before, producing almost same amount of electricity on average across panels (a) to (c). On the other hand, when these loads become gas-fired generation, the production becomes more volatile, its production levels being sensitive to the (varying considerably with the) intensity of the gas price shocks.

The change in the cost distribution among firms As shown earlier, the industry-level marginal cost curve is considerably disrupted after the retirement. This also indicates that there must be a disruption in the marginal cost among strategic firms, which has important implications for the competition. To show this, I examined the exogenous disruption in the marginal cost due to the plant retirement.

It is important to note that the change in the dispersion of marginal costs can arise from two different channels; an exogenous change directly caused by the retirement-induced merit order change, as well as the endogenous change in costs due to firm-specific quantity adjustments resulting from the change in market power. Since we are dealing with a piece-wise linear marginal cost structure, the change in market power leads to firms re-optimizing their quantity and as a result the marginal cost will change as a movement along the marginal cost curve.³³ As our focus is more on how the exogenous disruption in costs caused by the event results in different market power and market outcomes, we want to exclude the latter channel of cost adjustment that follows the change in the market power.

To distinguish between these two channels, I obtain exogenous changes in marginal costs after applying the retirement, at the strategic Cournot quantity (q_{st}) that strategic firms were producing before the retirement. That is, for $\mathbf{q}_{st,bf} = \{q_1, \dots, q_{N_{st}}\}$, I obtained $C'(\mathbf{q}_{st}) = \{C'(q_1), \dots, C'(q_{N_{st}})\}$ for before ($nort$) and after (rt) applying the retirement, i.e., $C'(\mathbf{q}_{st,bf})_{nort}$ and $C'(\mathbf{q}_{st,bf})_{rt}$, respectively. The difference between $C'(\mathbf{q}_{st,bf})_{nort}$ and $C'(\mathbf{q}_{st,bf})_{rt}$ reflects the change in the marginal cost of firms that were operating retired plants.³⁴

Three statistics are examined with the exogeneous cost distributions obtained: standard deviations, mean and the order of each firm's marginal cost relative to others. Figure 9 shows the change in the dispersion (standard deviation) and the mean for each (d, h) market. While a quite large variation exists across demand and gas price levels, a consistent

³³The link between market power and cost disruption has been addressed in Asker, Collard-Wexler, and De Loecker (2018) where they examined the productive inefficiency arising from market power by comparing the marginal cost distribution with and without the market power.

³⁴The cost distribution evaluated at the post-retirement strategic quantity ($\mathbf{q}_{st,af}$), which is the final change incorporating the endogenous quantity reoptimization, is different from this exogenous change.

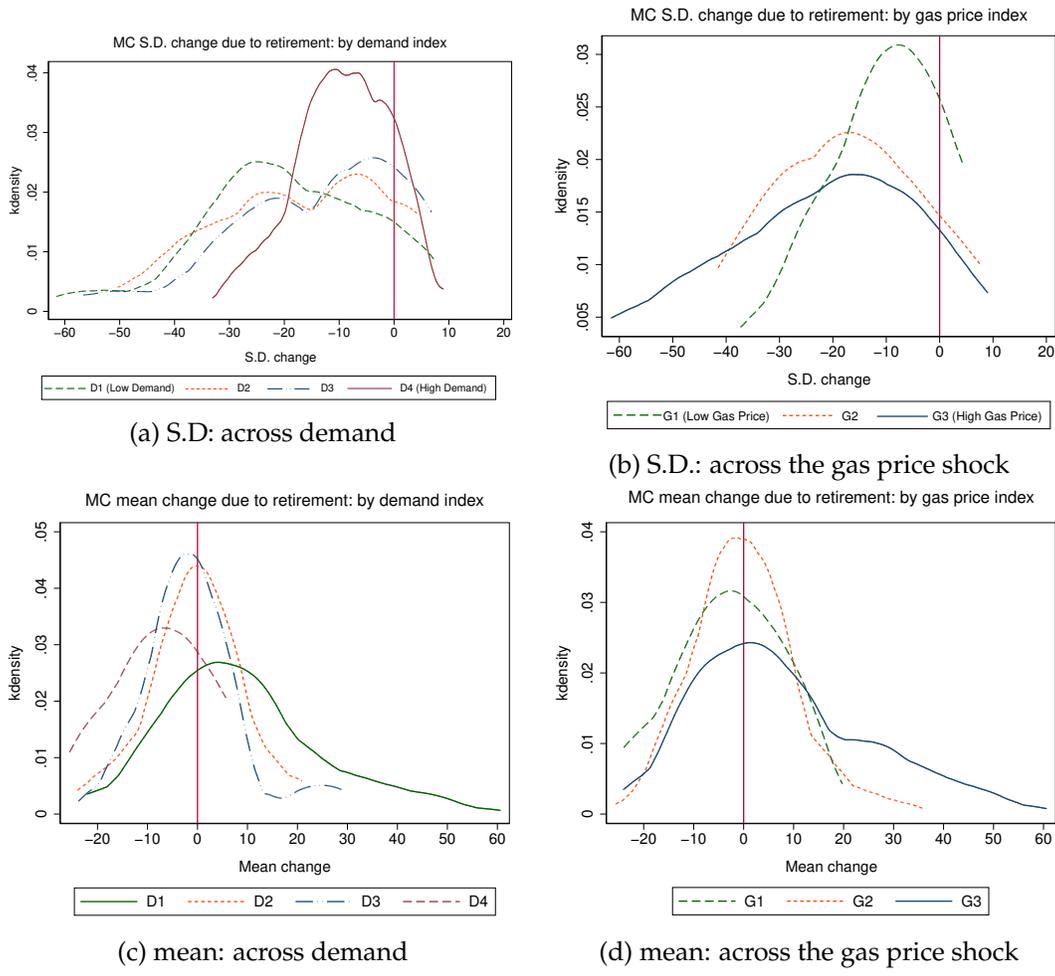


Figure 9: Change in the dispersion and the mean of marginal costs of strategic firms

pattern is that the retirement results in a reduction in the dispersion in most cases, as shown in panels (a) and (b), because the retired power plants are of low-cost. Panels (c) and (d) show that the average level of costs increases the most in low demand hours when baseload generators are most active, and when the gas price levels are high where the cost difference between the conventional baseloads and the gas-fired generator is more pronounced.

Moreover, the order of the marginal cost among strategic firms are disturbed quite significantly by the retirement. This is measured by ranking $C'(\mathbf{q}_{st,bf})_{nort}$ and $C'(\mathbf{q}_{st,bf})_{rt}$ based on the size, and comparing the change in the order of each firm's marginal cost.³⁵ Higher measure of "order disruption" is an indication of previously low-cost generator becoming relatively expensive units. Indeed, it was mostly the firms heavily concentrated in coal or nuclear generation that were able to supply at the lowest cost before the retirement, but the

³⁵I used the mean squared error of firm-level rank, reweighted by the number of strategic firms, as a measure the order change.

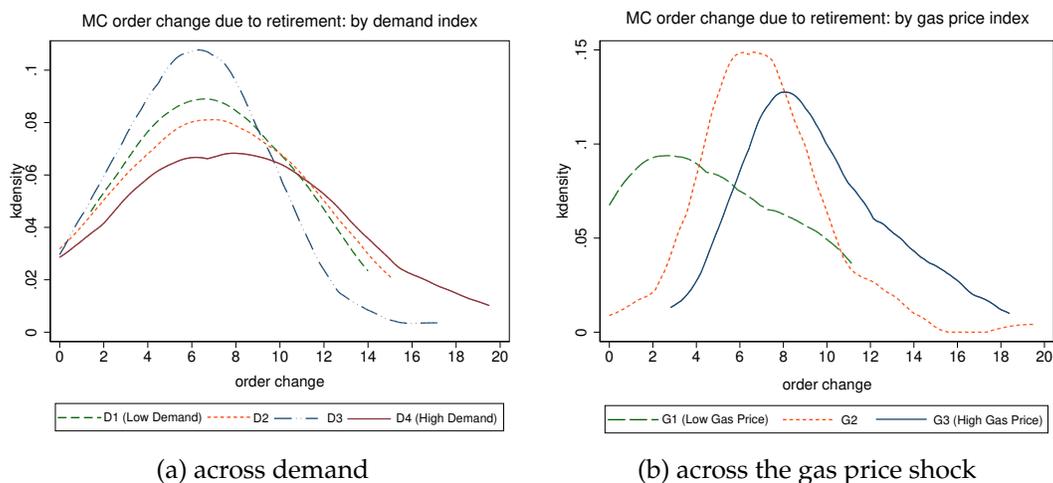


Figure 10: Change in the order of MC

new lowest-cost firms become those operating unretired baseloads or those highly concentrated in gas generation.

The change in the relative cost order among firms, coupled with the change in the average value of costs, are likely to affect strategic outcomes at the firm-level. And this could be one of the reasons why we find a change in market power in the transformed industry. I later explore the extent and the direction to which these documented changes in cost distribution are linked to the exercise of market power.

Firms having strong influence on market power Now we want to understand which types of strategic firms are responsible for the increased market power, and explore more the market conditions that enable these firms to do so. A small difficulty in analyzing the firm-level market power is that firms do not set their own prices in this quantity competition setting, thus using price-cost markup as a measure of firm-level market power is perhaps not suitable.

Here I focus on the fact that a strategic firm having substantial market power would adjust its quantity in an attempt to manipulate the market price. That is, firms' exercise of market power comes in the form of profitably withholding quantity (reducing the quantity produced) and still able to raise the market price.³⁶ In general, strategic withholding more applies to the quantity produced by strategic firms together, and measured as how

³⁶Such behavior is demonstrated in Borenstein and Bushnell (1999) where they study the strategic behavior of electricity generating firms in the U.S. wholesale electricity market. They argue that market share and the HHI measure based on the share may not always represent the extent of market power when some strategic firms withhold the production. Also, in Asker et. al (2018), the presence of market power in OPEC market is evidenced by the fact that OPEC countries together restrict production relative to their reserves, compared to non-OPEC countries.

much this quantity departs from the quantity that would be produced if these firms instead behave as price takers. I extend this concept to the firm level, and define firm-level withholding as a difference between a firm's quantity simulated in strategic Cournot equilibrium and the quantity simulated when firms acting as price takers (i.e., outcome in competitive equilibrium). The negative net strategic quantity, i.e., $q_{i,st}^* = q_{i,st} - q_{i,com}$, therefore, indicates a withholding of production at the firm level.

Again, we are interested in the *change* in the firm's strategic behavior that results from the retirement-induced industry transformation. Therefore, we examine markups of firms who additionally withhold their net strategic quantity after the retirement compared to the net strategic quantity they were producing before the retirement, but enjoy a higher markup by doing so. That is, for each (d, h) market, I find firms whose (i) net strategic quantity adjustment is negative in both the pre- and post-retirement states ($q_{i,st,pre}^* < 0$ and $q_{i,st,post}^* < 0$), (ii) the extent of withholding increases in the post-retirement state compared to the pre-retirement state ($q_{i,st,post}^* < q_{i,st,pre}^*$) and (iii) whose markup increases further as a result of withholding ($\text{markup}_{i,post} > \text{markup}_{i,pre} > 0$). The last condition, selecting those having their price-cost markup increasing, is necessary to make sure that the loss in profit by withholding quantity is offset by a large increase in the price-cost margin. I also verified that an increase in the price-cost markup of selected firms is associated with a profit increase.³⁷

Note again that by examining the change in the net strategic quantity q_i^* , we are taking care of the quantity response that naturally arises due to the change in the cost distribution even when a firm behaves competitively. This is especially important as our focus is on the plant retirement event that causes a disturbance in the industry-level marginal cost; the competitive quantity of firms even when dispatched in a cost-minimizing manner would change as a result of the merit order change.

The markups of selected firms explains the unilateral market power very well. That is, the correlation between the markups of all strategic firms and the $\Delta\Delta P$ is around 0.09, but increases above 0.5 on average when restricting firms to the selected ones. Therefore, I will mainly use the markups of these selected strategic firms for the subsequent analysis.

Firm-level markup and market environment Now we explore the relationship between the markups of selected strategic firms and some market variables known to be affecting firms' exercise of market power. Earlier, we have shown how market power differs across demand and gas prices. Here we want to find some variables that vary along with the change in demand and gas prices, and show how these are related to the markups of the

³⁷For this exercise, I computed the lower bound of net profit gain measured by $\Delta \text{profit} = \Delta \text{markup} \times q_{af} + \text{markup}_{bf} \times \Delta q$. Note that this is the lower bound of the profit gain since I did not fully account for the piecewise linear feature of the marginal cost curve, treating the marginal cost to be flat for all infra-marginal quantity. While the profit of all of the selected firms increases after withholding quantities, this is not always the case for other non-selected firms.

	(1)	(2)	(3)	(4)	(5)
	markup _{<i>i,pre</i>}	markup _{<i>i,post</i>}	Δ markup _{<i>i</i>}	Δ markup _{<i>i</i>}	Δ markup _{<i>i</i>}
Slope of residual demand	-4.28 (1.055)	-12.9 (1.745)	-8.39 (1.384)		-2.90 (0.974)
Gas generation share	-0.621 (0.06)	-1.207 (0.11)	-0.584 (0.09)		-0.182 (0.065)
Δ MC order				1.361 (0.247)	0.666 (0.318)
Δ MC s.d.				0.027 (0.027)	0.008 (0.027)
Δ MC mean				0.278 (0.062)	0.277 (0.062)

Notes: Standard errors in parenthesis. N = 305 for (1)-(3) and N = 284 for (4)-(5). This regression restricts the sample to markups of firms selected to having strong influence on market power by actively withholding quantity additionally after the retirement. There are at most two of such selected firms in each market (defined as market of day t and hour h). All the variables shown in the left column is measured at the market level. For specification (3), Δ total withheld quantity is used.

Table 11: Markup of selected firms: on various market variables

firm with greatest influence on market power among strategic firms.

Simple regression explores the relationship, the result of which is reported in Table 11. First two columns (1) and (2) report regression on pre-retirement and post-retirement markups of the selected firms on the market variables, where the regressions from column (3) use the change in markup, Δ markup_{*i*}. The results are not qualitatively different across (1) to (3), thus I will discuss the result based on Δ markup_{*i*} regression.

First, the slope of residual demand which represents how responsive the non-strategic (fringe) supply is to a price increase is an important determinant of market power as it limits strategic firm's ability to raise price by withholding quantity. As shown in column (3), higher the slope, less markup earned by influencing firms. Secondly, gas generation share is a variable that shows the percentage of production coming from gas-intensive firms (having 90 % of gas generation), therefore measures whether competitors of the influencing firm is concentrated in gas generating firms or not. As the competitors are more gas-intensive firms, the markup of the firm decreases.

Column (4) reports the regression done on cost distribution variables. The order change and the mean change of marginal cost strongly explains firm's markup increase. This result could explain our findings that the unilateral market power is larger when the market is affected by a larger gas price shock. While the pattern of the order change is quite similar across different demand levels, there is a clear increasing pattern across the intensity of the gas price shocks. The costs could be more dispersed and heterogeneous when gas prices are

Firm Type	No. of Firms	Total Capacity (MW)
Retired firm	5	8,090
To be Gas-intensive	3	3,950
To be Balanced	2	4,140
Non-retired firm		
Gas-intensive	7	11,600
Balanced	5	9,309

Notes: I restrict to firms having influence on market price; selected to have market power. Total capacity reports the sum of capacity of all types of fuel generators operated by firms that belong to each firm type category. Firms operating gas generation that amounts to more than 90 % of their total generation is categorized as “Gas-intensive” firms. “Balanced” firm refers to those having relatively large proportion of fuel types other than gas generators, mostly coal and nuclear generation. “Retired” firm refers to firms that own power plants that retired in our counterfactual simulation.

Table 12: Summary of Firms by Fuel Technology

high, so that the relative cost rankings could be significantly disturbed. Also, the mean of marginal cost increases the most on average in low demand hours, and as higher the gas price shock, as shown in Figure 9.

Which type of firms are responsible for the change in market power? While the wholesale electricity market is characterized by producing homogeneous output, considerable heterogeneity exists in the way firms produce electricity. Since we are concerned of the retirement of certain types of fuel technology and the exogenous changes to gas fuel prices, I explore the dispersion in fuel technology among major strategic players and examine which types of firms are more responsible for the change in market power. Specifically, I look at the type of firms identified to have a strong influence by withholding the most under the changing market environment.

Table 12 summarizes some basic heterogeneity among major firms. Note that we restrict our analysis to strategic firms that have a large presence by having considerable market share. Firms operating gas generation that amounts to more than 90 % of their total generation is categorized as “Gas-intensive” firms. The “Balanced” firm refers to those having relatively large proportion of fuel types other than gas generators, mostly coal and nuclear generation. The coal and nuclear generators operated by the balanced firms did not announce the plan to retire yet, thus not included in the retired plant list in our counterfactual simulation. “Retired” firm refers to firms that own power plants that retired in our counterfactual simulation. Three firms – grouped into “to be gas-intensive” – out of total five retired firms become gas-intensive (having 100 % of gas generation) after the retirement, whereas

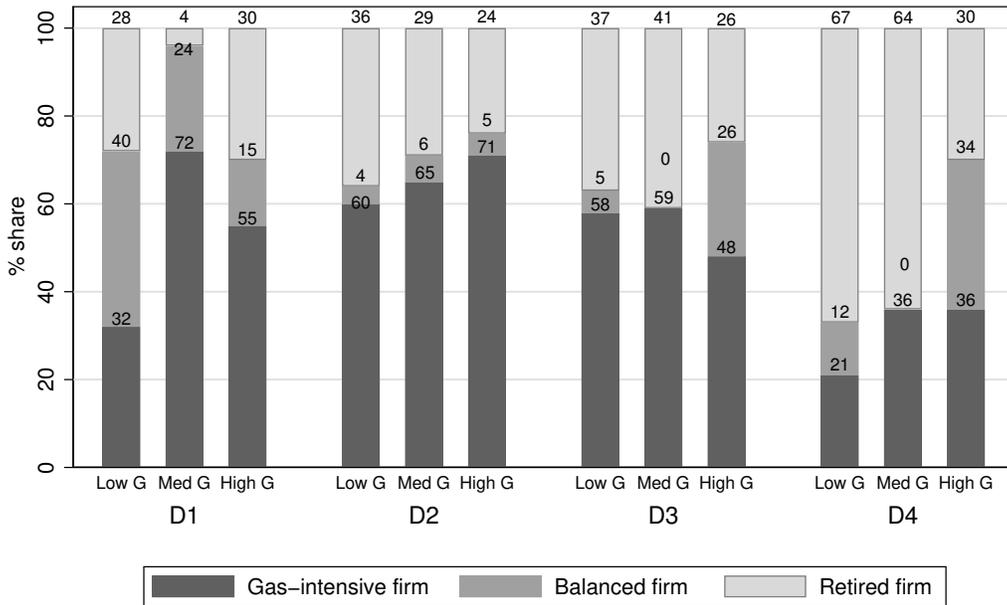


Figure 11: Percentage of selected strategic firm: by firm types

two firms – grouped into “to be balanced” – maintain a balanced generation mix after the part of the generation retires.

Figure 11 reports the percentage of firms selected to have a large influence on the price change, summarized for different demand and gas price bins. First takeaway from the graph is that gas-intensive firms that are not directly affected by the retirement – as they do not operate any of the base load generation – most actively engages in strategic withholding, over all demand range. Moreover, their overall presence increases further with the larger intensity of the gas price shock. On the other hand, “Balanced” and “Retired” firms’ ability to raise the price diminish gradually with the increase in gas prices. Therefore, the retirement gives increasingly more ability to the “Gas-intensive” firms especially when the market is under influence of a large gas price shock, which could be the main driving force of our finding of relatively large increase in market power for days with higher gas prices.

The cost and benefit of the retirement under high gas prices Given our findings, now we discuss what benefit the conventional baseloads were giving especially under large gas price shocks. First, as shown in Figure 8, the quantity produced by the constantly low-cost baseload plants were quite stable, on average, during the off-peak hours, regardless of the different levels of gas prices. Once these plants become gas-fired plants, the total quantity produced by these firms decreases in overall, and fluctuates with the changes in input costs driven by the gas price increase. That is, the quantity produced decreases further as the gas price increases, by up to 50 % on average. As a result, an increased amount of residual

demand will be allocated to the relatively higher cost firms not affected by the retirement.

When gas prices are high, the difference between the cost of coal or nuclear plant and the gas-fired plant is large. The retirement of coal or nuclear plant, in this case, will increase the average cost of strategic firms which further decreases the production. The larger the difference – the higher the gas prices, in other words –, the overall quantity reduction and withholding increases.

Finally, the higher gas price increases the cost dispersion, and makes residual demand (which depends on the non-strategic supply) less responsive to price. Not enough low-cost replacements around to meet the reduced quantity from the conventional baseload generation.

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A Appendix

A.1 Complementarity problem

This is how I converted the BMS version of the non-linear complementarity problem into Ryan (2014) version. The original expressions are as follows:

$$\frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \leq 0, \quad q_{it} \geq 0, \quad \left(\frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \right) q_{it} = 0 \quad (\text{A.1})$$

$$q_{it,max} - q_{it} \geq 0, \quad \lambda_{it} \geq 0, \quad (q_{it,max} - q_{it}) \lambda_{it} = 0 \quad (\text{A.2})$$

First, if $q_{it} \in (0, q_{it,max})$, then because q_{it} is positive $\left(\frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \right) = 0$ is implied by the third condition of equation (A.1). Also, because $q_{it,max} - q_{it} > 0$, $\lambda_{it} = 0$ is implied by the third condition of equation (A.2). Thus, $\frac{\partial \pi_{it}}{\partial q_{it}} = \lambda_{it} = 0$ holds as $\left(\frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \right) = 0$.

Second, if $q_{it} = q_{it,max}$, then $\lambda_{it} \geq 0$ from the third expression of equation (A.2), and since $q_{it} > 0$, it must be that $\left(\frac{\partial \pi_{it}}{\partial q_{it}} - \lambda_{it} \right) = 0$ from the third condition of equation (A.1). Therefore, $\frac{\partial \pi_{it}}{\partial q_{it}} = \lambda_{it} \geq 0$ holds.

Finally, if $q_{it} = 0$, then $q_{it,max} - q_{it} > 0$ unless $q_{it,max}$ is zero which is not the case. Therefore, $\lambda_{it} = 0$ from the last condition of equation (A.2). And since $\frac{\partial \pi_{it}}{\partial q_{it}} \leq \lambda_{it}$ holds as implied by the first condition of equation (A.1), $\frac{\partial \pi_{it}}{\partial q_{it}} \leq \lambda_{it} = 0$ holds.

As a result, we have an expression for mixed complementarity problem (MCP):

For $\forall i \in \mathcal{F}$

$$\begin{aligned} 0 < q_{it} < q_{i,max} &\Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} = 0 \\ q_{it} = 0 &\Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} \leq 0 \\ q_{it} = q_{i,max} &\Rightarrow \frac{\partial \pi_{it}}{\partial q_{it}} \geq 0 \end{aligned} \quad (\text{A.3})$$

This matches the standard specification of MCP problem. Three pieces of data are necessary which are the upper bounds u , lower bounds l and the function F . The general form of MCP problem is described as below:¹

(MCP) Given lower bounds l , upper bounds u and a function $F : R^n \rightarrow R^n$, find $z \in R^n$

¹Taken from Ferris and Munson (1998)

such that precisely one of the following holds for each $i \in \{1, \dots, n\}$:

$$\begin{aligned} F_i(z) = 0 & \quad \text{and} \quad l_i \leq z_i \leq u_i \\ F_i(z) > 0 & \quad \text{and} \quad z_i = l_i \\ F_i(z) < 0 & \quad \text{and} \quad z_i = u_i \end{aligned} \tag{A.4}$$

Therefore, the function F that enters the PATH solver must be $-\frac{\partial \pi_{it}}{\partial q_{it}}$.

A.2 BMS(2008) methodology for estimating the residual demand curve

In Bushnell, Mansur and Saravia (2008), they estimate β – the price elasticity of non-strategic supply ($Q_{ns,t}$) – using the over-time variations in quantities of fringe supply and the net imported electricity. In addition to the daily slope estimates that are used in the main analysis, I also estimated β following the methodology used in BMS (2008). The specification is shown below:

$$\begin{aligned} q_i^{fringe} = & \beta \ln(p_t) + \rho \text{Sample}_t + \theta \ln(\text{spot gas price})_t + \sum_{j=2}^7 \delta_j \text{Daytime}_{jt} + \sum_{h=2}^{24} \pi_h \text{Hour}_{ht} \\ & + \sum_m^M \lambda_j \text{Month}_{mt} + \sum_y^Y \lambda_y \text{Year}_{yt} + \varepsilon_t \end{aligned}$$

For fringe supply, q^{fringe} , I used the sum of quantity supplied by generating firms that I categorized into non-strategic firms and the quantity of net import (import - export). The parameter β captures the responsiveness of fringe quantity to a price increase.

However, this method is not perfectly suitable in our setting where different levels of gas prices cause significant disruption to the merit order of dispatch and the price responsiveness of fringe supply. For example, the estimate of the above regression differs across samples with and without the gas price shock, where the responsiveness β is smaller when gas prices are higher. This result supports the use of daily residual demand estimate that more accurately reflects the heterogeneity in market conditions across days in the sample.

A.3 Strategic Response: observed equilibrium

Now, we separately look at the response of firms that operate the baseload generation versus those firms not operating the baseload generation. In Figure A.1, I plot distributions of net total quantity response of two strategic firm groups, against demand (low and high) and gas price (input cost shocks) levels to show how such responses differ along these dimensions.

Comparing (a),(c) and (e) shows how firms' responses change as demand increases, having fixed the gas price to low level which makes gas-fired generators' cost comparable to that of coal-fired generators. Interesting pattern is that, when demand is low (off-peak hours), strategic firms operating mainly the non-baseload, gas-fired power plants tend to

withhold quantity, while firms operating baseload generation produces close to or more than the competitive level. It is known that baseload generators tend to produce at below cost, thus producing more than expected under competitive equilibrium, due to large start-up costs and the forward supply obligation (Bushnell et. al, 2008; Reguant, 2014). Corresponding to these findings, the total net quantity supplied by firms operating the baseload plants are mostly positive in Panel (a) which we normally face during off-peak hours in the wholesale market. On the other hand, gas-fired plants with low start-up costs are rather flexible in their production and they tend to withhold quantity. That is, it is better for these major firms to withhold quantity, at the risk of forgoing the chance of being able to produce, to earn higher unit price for the product. In the auction setting, such withholding is equivalent to submitting price bids above marginal cost, given the same quantity bids. This explains why we may observe strategic prices that are lower than competitive prices in the low-demand, off-peak period; the withheld quantities by these strategic firms without baseload generation are met by the baseload generators willing to oversupply at a lower price bid. However, as demand increases, such withholding is less pronounced because firms with the baseload generators also compete with their non-baseload generators. As shown in panels (b) and (c), net quantity changes of both firm groups overlap with higher demand levels. Moreover, firms without baseload generation produces more than expected under competitive equilibrium.

On the other hand, with higher gas prices, withholding of quantities by firms without the baseload generation decreases even in low demand, and oversupply of baseload firms is less pronounced as well, as shown in panels (b), (d), and (f). Higher gas prices widens the gap between the costs of baseload generators and the gas-fired generators, therefore leaves a room for baseload guys to not having to over supply below the costs. As with higher demand, the firms without baseload generation withhold less than baseload firms, while baseload firms withhold relatively more compared to low demand.

A.4 Additional Graphs

A.5 Plant retirement and the industry-level cost distribution

Different types of retirement and its impact on the marginal cost distribution Retirement of coal plants and nuclear plants have different types of impacts on the marginal cost distribution. A replacement of zero-cost nuclear plants with the gas-fired plant having positive marginal costs would lead to an inward shift of the industry marginal cost curve, with the basic shape of the curve not affected much. Also, such shift is observed regardless of the shock: with and without the cost shock. On the other hand, the effect of coal plant's retirement on marginal cost curve depends on whether or not the gas prices are at the normal level of \$ 4/mmbtu, which is similar to the coal price. That is, when prices of both fuels are similar to each other, replacement of coal plants with gas plants have minimal effect on the distribution of the cost curve. However, retirement significantly disrupts the shape of the curve as well as the ordering of the units when the levels of gas prices increase above the normal level due to the shock.

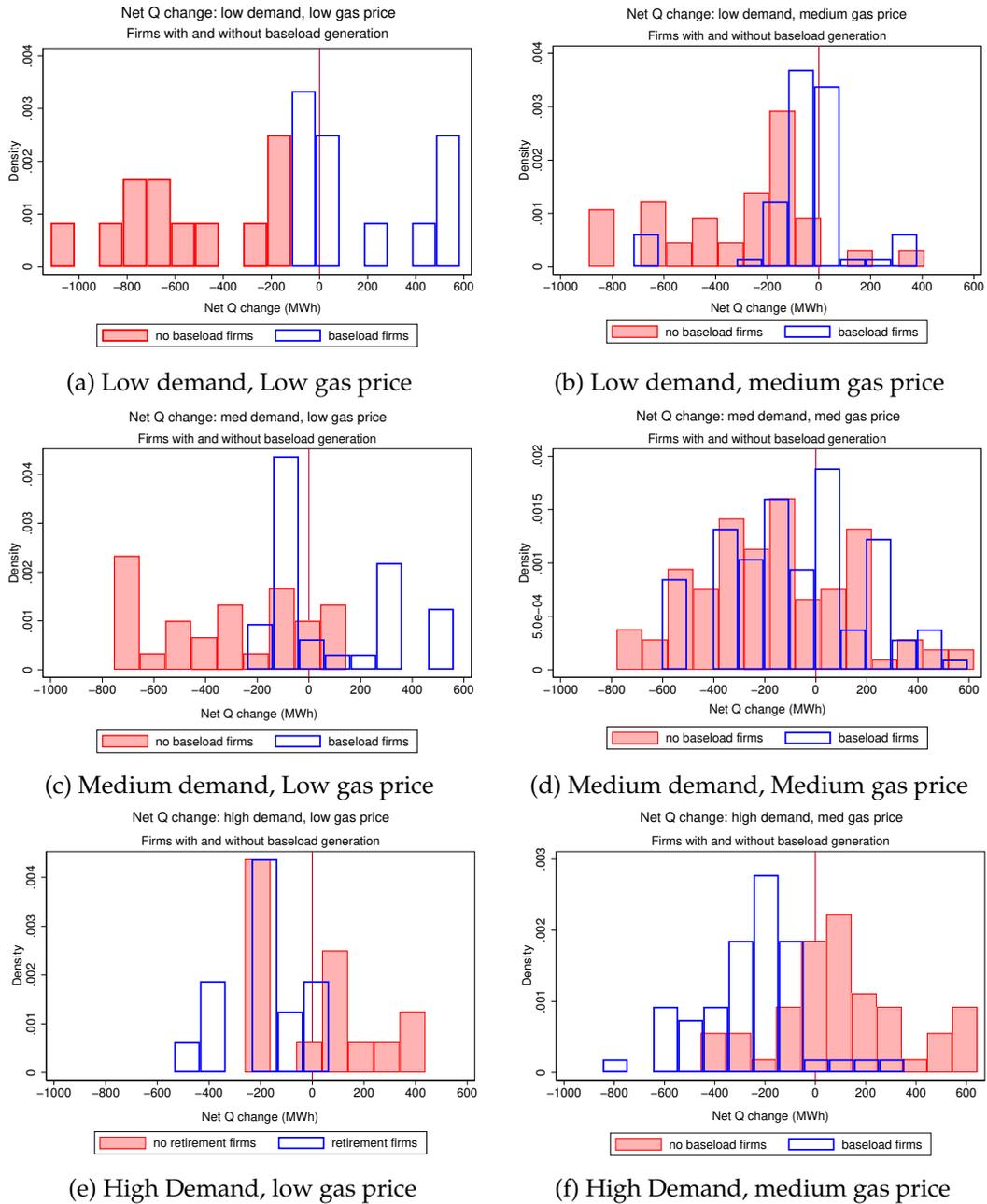


Figure A.1: Net quantity difference (observed - competitive): Strategic firms with and without baseload power plants

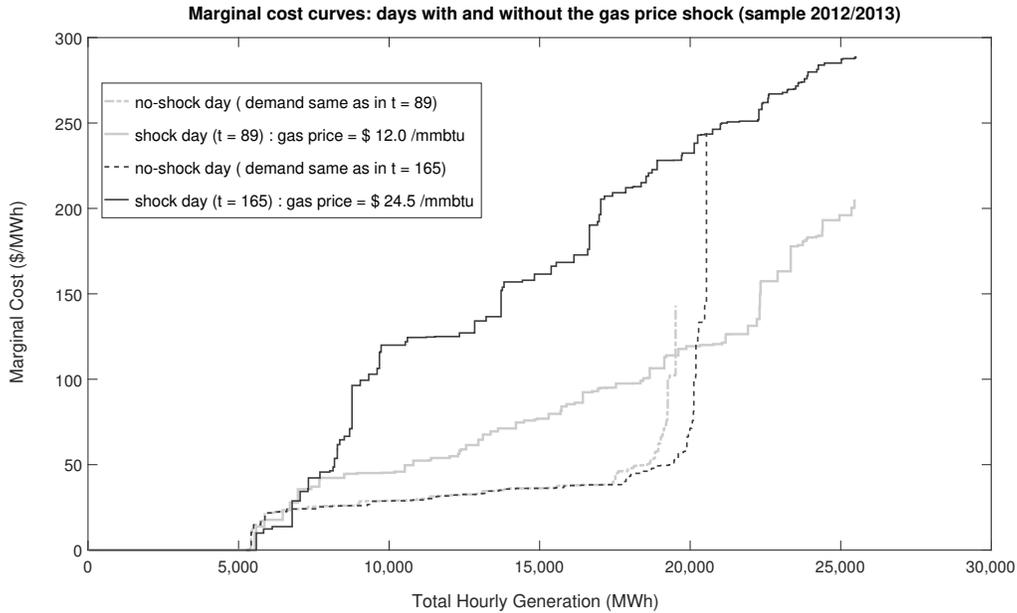
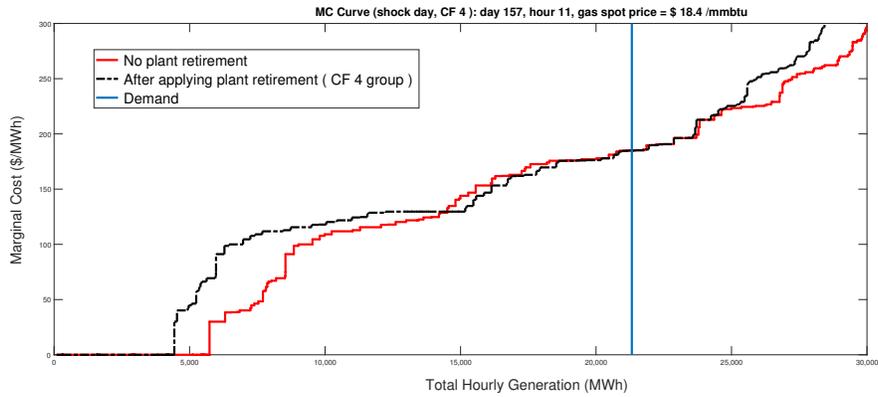


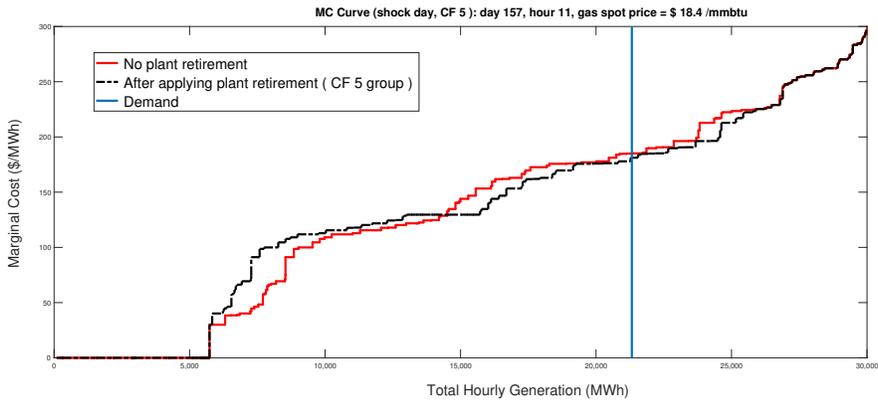
Figure A.3: Marginal cost curves: days with and without the gas price shock

Figure A.4 illustrates this. As shown in Panel (A.4c), nuclear retirement simply shifts in the distribution, and most significant changes occur at the low-demand region (left portion of the curve) whereas the distribution around the equilibrium (where demand intersects with the marginal cost curve) does not change much after the retirement. On the other hand, as shown in Panel (A.4b), coal plant retirement leads to a significant disruption of the marginal cost distribution; the slope of the distribution curve changes uniformly over all quantity levels. When both types of retirements are combined, which is presented in Panel (A.4a), disruption in the marginal cost distribution (curve) becomes most salient.

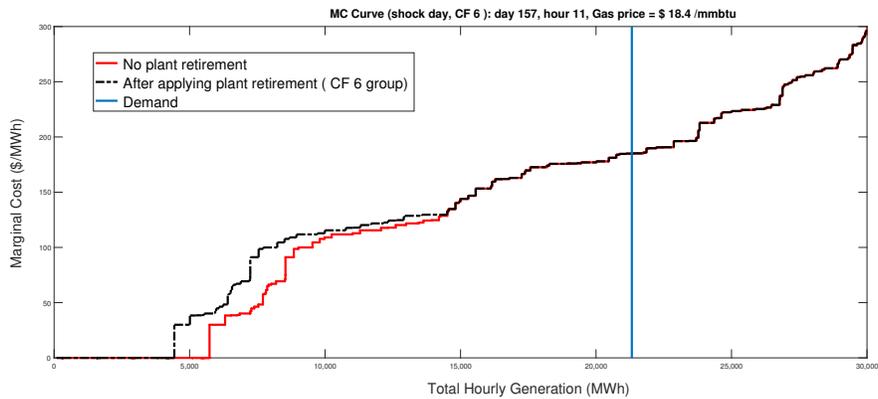
Where the market clearing prices will be set, which is determined by the aggregate level of electricity demand, is an important factor since the slope change does not occur uniformly across demand levels. This implies that the retirement's effect on market outcomes and competition would be more salient if the cost distribution is disrupted closer around the market clearing point. Figure A.5 demonstrates this point by presenting cost distributions of two different days. In the first case shown in Panel (A.6a), competitive price is likely to increase because the marginal cost curve around the initial equilibrium – where demand intersects with the marginal cost curve – shifts up. Moreover, we observe in this case that the distribution of costs changes around the equilibrium. On the other hand, in the second case shown in panel (A.6b), the cost curve does not shift much around the initial equilibrium and the disruption of the marginal cost distribution is also not significant. Consequently, we can expect the changes in both competitive price and the degree of strategic competition due to retirement to be minimal in this case.



(a) Both Nuclear and Coal Plant Retirements Applied



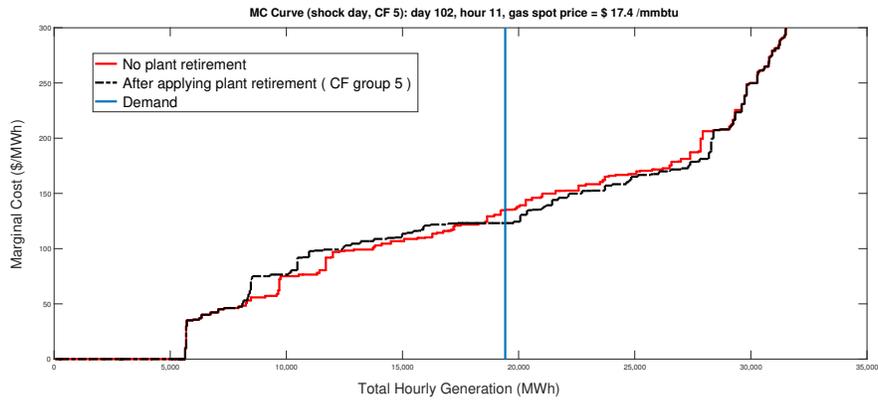
(b) Coal Plant Retirements Applied



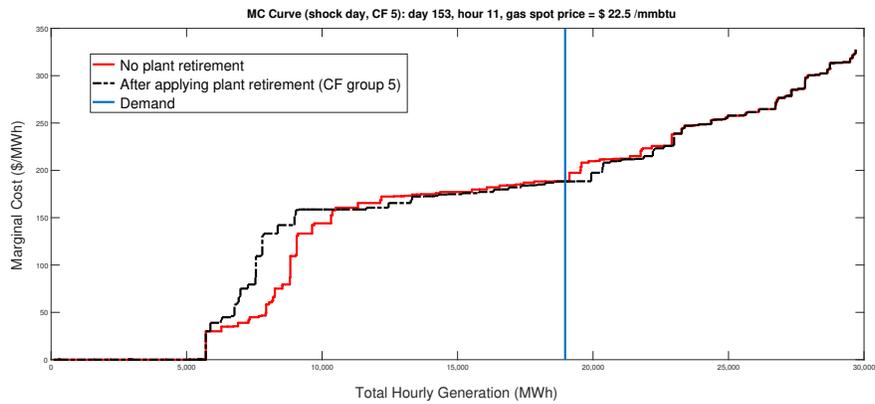
(c) Nuclear Plant Retirements Applied

Figure A.4: Different Impacts on Industry Marginal Cost Curve: Nuclear and Coal Plant Retirements

(a) Example of a significant cost distribution change around the equilibrium due to retirement



(b) Example of minimal change in slope around the equilibrium due to retirement



Notes: Only the retirements of coal-fired power plants are applied when plotting graphs shown here.

Figure A.5: Different impacts depending on demand and shock intensity