

Investment, Emissions, and Reliability in Electricity Markets*

PRELIMINARY AND INCOMPLETE

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Abstract

How should we design electricity markets to promote investment in clean energy while maintaining a reliable electricity grid with a low likelihood of blackouts? These two topics are related because zero-emission renewable energy sources, such as wind and solar, are intermittent. Their supply is less reliable than traditional, greenhouse gas-emitting generators like coal and natural gas, so an increasing share of renewables can potentially lead to increased blackouts if the addition of intermittent renewables causes these generators to retire. Quantifying the full impact of electricity market policies therefore requires an understanding of how investment responds in equilibrium. To that end, I build a structural equilibrium model of investment and dis-investment in generators of different energy sources. Oligopolistic firms make dynamic decisions to build or retire generators based on the profits they receive from wholesale electricity markets, which respond to the composition of generators in the market. I estimate this model using data from the Western Australia Wholesale Electricity Market and use the estimated model to simulate investment and production under counterfactual policies. Carbon taxes reduce emissions but, for certain values, can cause an increase in the likelihood of blackouts by causing retirement of coal and some natural gas generators. Subsidizing capacity prevents this from occurring, but at the expense of a high level of emissions. Using both policies together, however, keeps high-emitting but reliable generators in the market but prevents them from being used unless necessary, substantially lowering emissions while keeping the likelihood of blackouts low. I also explore alternative environmental policies, which are less effective at reducing emissions but have a lower cost to consumers.

Keywords: electricity, renewable energy, market structure, investment, capacity payments, greenhouse gas emissions

JEL Classification: L11, L13, L94, Q41, Q52

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1 Introduction

The electricity industry faces two major challenges. First, the sector emits more greenhouse gases than any other sector, accounting for a quarter of total global emissions (IPCC, 2014). Second, when demand for electricity exceeds electricity supplied, blackouts occur, which are extremely costly events, as evidenced by the events in Texas in February 2021 in which 70% of households lost power.¹ Increasingly cost-competitive renewable energy sources can solve the first issue, but, because they are intermittent, can exacerbate the second. This paper studies how to optimally regulate electricity markets to balance these environmental and reliability costs.

This paper makes three major contributions. First, I develop a dynamic equilibrium framework for understanding how electricity market policies impact investment and production in electricity generators of different energy sources (e.g., coal, natural gas, wind).² Oligopolistic firms build or retire generators based on the profits they receive from the generators in wholesale electricity markets. The model endogenizes emissions, blackouts, costs, and prices, allowing me to determine the equilibrium impact of electricity market policies on welfare. Second, I apply this framework to the electricity market in Western Australia, for which the issues of reliability and emissions are particularly salient due to its lack of a grid connection to other electricity markets and heavy reliance on coal. I show how to estimate the model using production and investment data from this market. I then use the estimated model in a third contribution to quantify how policies aimed at increasing reliability or reducing emissions impact welfare. I use this quantification to determine optimal policy for reducing blackouts and emissions.

The first type of policies I consider are aimed at increasing reliability. Specifically, I evaluate the impact of capacity payments, which are fixed payments to generators in proportion to their *capacities* (in addition to revenue received from actually producing electricity) and the primary policy tool grid operators have used for reducing blackouts. Markets utilizing these payments include the market studied in this paper, Western Australia, as well as markets in the United States (including PJM, NYISO, and New England ISO), Europe (including Spain, France, Ireland), and others across the globe. These payments seek to fix underinvestment in capacity. Underinvestment is a result of end-consumers being unresponsive to the wholesale

¹<https://www.texastribune.org/2021/03/29/texas-power-outage-ERCOT/>

²The framework is specifically for “restructured” electricity markets in which independent generators sell electricity to the grid. This type of market stands in contrast to vertically integrated markets in which the grid operator also owns the generators. Many electricity markets were restructured in the 1990’s, and these are the markets that I focus on in this paper. See Borenstein & Bushnell (2015) for a history and evaluation of restructuring. Although this review of restructuring is specific to the US, restructuring has happened across the globe, including in the electricity market that I study, Western Australia.

spot market price since they demand electricity not based on this price but rather a constant retail electricity price. If consumers demand more electricity than there is available capacity, then they must be rationed to equate supply and demand. Since consumers cannot be rationed based on their valuations of electricity consumption, firms do not receive the value to consumers of avoiding a blackout that an investment creates. There is thus a positive externality associated with generator investments, and under-investment results (Llobet & Padilla, 2018; Fabra, 2018).

The second type of policies I consider are environmental policies aimed at reducing greenhouse gas emissions. Approaches governments have adopted are varied. Common policy tools include renewable investment subsidies, carbon taxes, and renewable production subsidies. I use the estimated model to compare the impact of these environmental tools on emissions, blackouts, and total welfare. Attempts to implement these policies have often met political headwinds as a result of the perceived distributional impact of these policies. In response to these political constraints, I evaluate how the benefits and costs of a policy are shared by producers and consumers.

The impact that a policy has on reliability depends on the total investment in generators of different energy sources, and the impact on emissions depends on which of those generators are used. As firms build more generators, the electricity-generating capacity increases, reducing the likelihood of blackouts. It is not this extensive margin of capacity that directly determines emissions, however, but rather the intensive margin of how much of that capacity is used to produce electricity. If, for example, electricity is primarily generated using coal and natural gas, the emissions will be substantially higher than if it is generated primarily using wind, regardless of the total capacity for each energy source. For a policy to reduce both reliability and environmental costs, it must yield a high level of investment in reliable generators but induce those generators to produce only when low-emission generators are unavailable.

The returns to investment depend on the investment and production decisions of other firms, necessitating the equilibrium model of investment developed in this paper. Firms in the model produce electricity in wholesale electricity spot markets, resulting in a stream of profits, and these profits depend on the investment levels in different energy sources. Firms make investment decisions by trading off the returns to an investment (the increase in wholesale profits) with the cost of new generators. A policy could impact equilibrium profits either directly, by changing the returns in the wholesale market (such as a carbon tax, which makes electricity produced by emissions-intensive sources more costly), or indirectly, by changing the costs to investment (such as a renewable investment subsidy, which only changes profits through the changes in generators competing in the market). My model incorporates three crucial features that determine how investment responds to the policies studied in this paper:

market power, capacity constraints, and declining renewable costs.

The wholesale profits depend crucially on the first feature, the level of market power. A wide literature has documented the presence of market power in electricity markets.³ Firms in my model are therefore oligopolistic, which creates a wedge between the social benefit of production in the wholesale electricity market and the private benefit. This wedge affects productive efficiency in the short-run because electricity is not produced in a cost-minimizing way. In the long-run, demand responds to prices, so the wedge also affects allocative efficiency since the wedge causes prices to exceed marginal costs. Market power also distorts firms' incentives to invest. In making investment decisions, firms consider the impact an investment in generators has on wholesale market prices. In a homogeneous good market, such as electricity, this distortion can result in overinvestment due to business stealing. In the case of electricity markets, however, firms may underinvest due to the positive externality associated with capacity that results from the lack of short-term price responsiveness. The equilibrium investment level depends crucially, therefore, on the presence of market power.

Capacity constraints are another important feature of electricity markets; blackouts occur only when demand exceeds total capacity. In the oligopoly game played by generators, these capacity constraints are a multidimensional state variable that greatly increase the difficulty of solving for equilibria.⁴ I provide an algorithm in this paper that simplifies the computation of an oligopolistic wholesale market equilibrium with generator capacity constraints. The algorithm substantially reduces computation time, making it tractable to solve for the stream of wholesale profits that results from many different generator investment levels and thereby nest oligopolistic wholesale profits into a model of investment.

The third feature of the model is declining generator investment costs of renewables. Wind and solar have experienced a tremendous decline in the cost of new generators. Declining costs provide an incentive for firms to wait to invest in new generators—even if it would be profitable to do so today—since they could increase their net profits by waiting for the cost to decline further. I incorporate this incentive by using a non-stationary dynamic model of investment since the decision to invest today depends on the future stream of profits as well as future investment costs. Firms have market power and are therefore strategic in their investment decisions, meaning that firms' investment decisions form a dynamic non-stationary oligopoly game in generator portfolios.

³See, for example, [Borenstein *et al.* \(2002\)](#), [Sweeting \(2007\)](#), [Bushnell *et al.* \(2008\)](#).

⁴The wedge between private and social benefits of production that results from market power means that which generators' capacity constraints bind is a function of residual demand curves, and residual demand curves are a function of which generators' capacity constraints bind. In contrast, in the competitive case, which generators' capacity constraints bind is a function of the market demand, but the market demand does not depend on which generators' capacity constraints bind.

I estimate the model described above using data from the electricity market in Western Australia. Western Australia provides an ideal case study in the environmental and grid reliability issues that motivate this paper. Western Australia has a particularly emissions-intensive grid but has experienced substantial entry of wind generators recently. Additionally, it is geographically isolated, meaning that its grid is not connected to the those in the rest of Australia. Lacking a grid connection, Western Australia cannot trade electricity with other markets, and therefore blackouts are a major concern. For this reason Western Australia adopted capacity payments to ensure sufficient capacity, and the size of these payments has varied considerably over time, providing useful variation for estimation.

I estimate the model in two stages. In the first stage, I estimate the process governing the evolution of wholesale production costs and demand in the short-run using a Tobit-like strategy to accommodate capacity constraints. I then use these estimates to construct expected profits as a function of generator portfolios. In a second stage, I use the model of the dynamic investment game and a full-information approach in which I use the likelihood implied by the model to estimate fixed generator costs. Dynamic games generally create issues for using a full-information maximum likelihood approach due to their multiplicity of equilibria and computational burden. I use stochastic alternating moves and a final period of investment, similarly to [Igami & Uetake \(2020\)](#), to simplify computation and ensure uniqueness of the equilibrium.

Using the estimated model, I study the equilibrium impact of carbon taxes, renewable investment subsidies, and capacity payments. My results suggest that using environmental policies alone results in substantial costs from blackouts, and using capacity payments alone result in a large environmental externality. Because wind is less reliable than thermal generators, environmental policies that either tax carbon or subsidize wind investment can increase the likelihood of blackouts because they cause a decline in the level of gas and especially coal capacity. Capacity payments keep the blackout likelihood at a low level, but fail to incentivize investment in non-carbon intensive technologies, resulting in substantially more emissions than even in a *laissez-faire* world.

Using a carbon tax and capacity payments jointly can keep blackout likelihoods low and incentivize wind investment and cleaner production. The capacity payments target the extensive margin—the level of capacity available in the market—and keep coal and gas generators from exiting the market when their production becomes relatively more expensive, and this high level of capacity keeps the likelihood of blackouts low. The carbon tax impacts the intensive margin and incentivizes production from relatively low carbon intensive technologies (e.g., gas instead of coal).

I also consider whether renewable investment subsidies achieve similar results to those of

carbon taxes. I find that because renewable investment subsidies impact only the extensive margin, they are poor substitutes for a carbon tax. They fail to make coal relatively more expensive than gas, and they even fail to induce as much wind investment (although at high levels still induce substantially more investment than in a world without investment subsidies or carbon taxes).

Related Literature Equilibrium investment levels depend on the wholesale profits firms receive for a given set of generators. The modeling of wholesale markets used in this paper is influenced by an extensive literature that studies competition in electricity markets. This literature goes back to the early days of restructured electricity markets, measuring markups in wholesale electricity markets due to imperfect competition (Wolfram, 1999; Borenstein & Bushnell, 1999; Bushnell *et al.*, 2008), and more recently using bidding data from wholesale auctions to study strategic behavior (Hortaçsu & Puller, 2008) and also estimate production costs (Wolak, 2007; Reguant, 2014). This paper uses similar methods as some of the aforementioned papers (particularly Bushnell *et al.* (2008)) to characterize market power as a function of capacity available in the market.⁵ This paper is therefore related to papers studying the equilibrium impact of adding renewables to the grid (Gowrisankaran *et al.*, 2016; Jha & Leslie, 2019; Karaduman, 2020b), the addition of utility-scale batteries (Karaduman, 2020a), and power plant closures (Davis & Hausman, 2016; Kim, 2020).

The model of wholesale profits is nested into a model of generator investment. To the best of my knowledge, this is the first paper to model oligopolistic equilibrium investment in electricity generators. Butters *et al.* (2021) develops a model of competitive investment in utility-scale batteries, but this paper differs from Butters *et al.* (2021) in two key ways that allow me to consider different policies. First, I endogenize the investment of all energy sources in the market (rather than just batteries).⁶ Second, I study investment with firms that have market power rather than competitive firms, which the literature outlined in the previous paragraph shows is common across markets.

In order to study the impact of policies on oligopolistic firms' investment and production decisions, I adopt techniques developed in the empirical dynamic games literature. Two closely related papers are Ryan (2012) and Fowle *et al.* (2016), which study environmental regulation in the cement industry. Similarly to these papers, I consider dynamic investment decisions among oligopolistic firms and the impact of environmental policy on equilibrium investments and emissions. Unlike these papers, investment is in multiple different technologies (e.g., coal,

⁵See section 3.1 for a detailed discussion of how the model relates to those previously used in the literature.

⁶There are no utility-scale batteries in the Western Australia market during the timeline I study. Since I do not study the impact of batteries, my model of wholesale market operations also differs significantly from that employed by Butters *et al.* (2021).

gas, wind), and the market is nonstationary (due to declining costs of renewable generators). That latter point, along with data constraints, is what causes me to adopt a different estimation strategy, instead following [Igami & Uetake \(2020\)](#). [Igami & Uetake \(2020\)](#) study mergers in the hard disk drive industry, and, similarly to this paper, observe a single industry in a non-stationary environment, in which the action of interest (mergers for them, generator investment in this paper) is observed infrequently. They make restrictions to the timing of the game that makes a full-information solution tractable, and I follow by making similar restrictions, detailed in section 3.

This paper is also related to a literature on reliability policy. A theoretical justification for capacity payments has been developed by [Joskow & Tirole \(2008\)](#) and [Fabra \(2018\)](#), and [Joskow \(2008\)](#) studies such payments in markets with imperfect competition.⁷ This is, to the best of my knowledge, the first empirical study to examine investment and retirement in electricity generators. This paper also considers the interdependence between reliability and environmental policy. [Wolak \(2021\)](#) considers how increasing intermittent renewables affect how electricity markets should compensate reliability. This paper considers this question in a model of investment while also considering how these policies choices impact greenhouse gas emissions.

Outline The paper is organized as follows. Section 2 provides institutional details on the Western Australia electricity market, describes the data, and presents descriptive statistics about the electricity market. Section 3 presents the structural model, section 4 the estimation method, and section 5 the estimation results. In section 6 I describe and present the counterfactuals. Finally, section 7 concludes.

2 Institutional Details and Data

2.1 Western Australia Electricity Market

Western Australia’s Wholesale Electricity Market (WEM) supplies electricity to southwestern Australia via the South West Interconnected System electricity grid, which includes the city of Perth and the surrounding area. Figure 13 in Appendix A.1 presents a map of this electricity grid. The WEM serves over one million customers and supplies roughly 18 terawatt hours of electricity every year. The South West Interconnected System is geographically isolated and

⁷See also [McRae & Wolak \(2020\)](#); [Teirilä & Ritz \(2019\)](#) for case studies in the impact of capacity payments under imperfect competition.

therefore not connected with other grids in the country, preventing the WEM from trading electricity with other markets.

In September 2006, the Western Australian electricity industry went through a restructuring, moving from a vertically-integrated utility company that generated, distributed, and sold electricity to a market with independent generators selling electricity to the grid (now owned by a separate state-owned company). This resulted in the creation of the WEM, which is operated by the Australian Energy Market Operator. Following the restructuring, independent generators sell electricity to retailers. This can either happen through bilateral contracts or through a day-ahead auction. Generators also receive capacity payments, described in detail in the following section.

The data begin with the commencement of this restructured market and are described in detail in section 2.3. Throughout the sample period, almost all electricity sold on the grid has been generated by one of three sources: coal, natural gas, and wind, collectively making up 98.5% of all electricity generated.⁸ These energy sources will therefore be the focus of this paper.

2.2 Capacity Payments

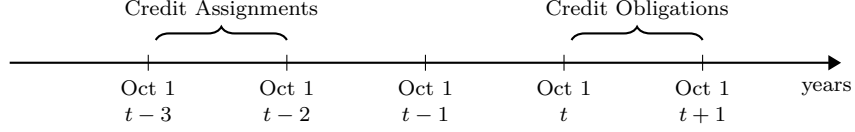
The WEM, since its commencement, has used capacity payments based on a system of allocating capacity credits, called the Reserve Capacity Mechanism. A capacity credit corresponds to a megawatt (MW) of certified electricity generation capacity that a firm commits to make available in the wholesale market. The grid operator chooses the price of a capacity credit, which varies from year to year, and firms choose a level of capacity for which to receive capacity credits. Firms are then contractually obliged to make available at least as much electricity as they have capacity credits or otherwise pay a penalty.⁹

At the beginning of a capacity year (which runs from October 1 to September 30), the grid operator announces a capacity credit price. These credits are valid for the capacity year three years following. For example, if on October 1, 2010 the grid operator announces a capacity credit price, then these credits commit a firm to produce in the year from October 1, 2013 through September 30, 2014. In the same year as the price is announced, firms decide whether

⁸Western Australia also has substantial rooftop solar, as described in [Jha & Leslie \(2019\)](#), but I focus on utility-scale generation, of which solar makes up only 0.9% of generation. Rooftop solar impacts the distribution of demand for electricity from the grid. In my model and counterfactuals, I allow for this distribution to change over time as rooftop solar penetration increases.

⁹Making electricity “available” is not the same as actually producing that level of electricity. In practice, firms bid quantities and prices in an auction with a price cap. Firms are required to bid at least as much electricity as they have capacity credits, with no limit on the prices other than the universal price cap. Failing to make electricity available is mostly due to generator outages.

Figure 1: Timeline of capacity credit for capacity year t to $t + 1$



to request capacity credits, and credit allocations are finalized by the end of the first capacity year.¹⁰ Once the fourth capacity year begins, firms are under their availability obligations according to the number of capacity credits they hold for that year. Wholesale markets occur in half-hour intervals, and firms pay a penalty if they fail to make their committed capacity available in an interval. Figure 1 depicts the timeline described above.

2.3 Data

The data come from the Wholesale Electricity Market and are provided by the Australia Energy Market Operator (AEMO). The data include information on the short-term wholesale market, including market prices, generation quantities, and generator outages at half-hourly intervals. These data are complemented by data from AEMO on capacity payments (both market prices as well as capacity credit allocations by generator) and generator investment decisions (including dates of entry or retirement, energy source that powers the generator, and generator owner).¹¹ Table 1 summarizes the data described above.

Figure 2 plots the three energy sources that make up the vast majority of electricity generation over time, measured both in terms of capacity (left panel) as well as the energy actually generated (right panel). Over the course of the sample, coal has experienced a small but notable decline, replaced by natural gas and wind. Figure 3 plots wholesale market prices and quantities over time. The solid blue line represents the mean price/quantity, and the light blue lines represent 10th and 90th percentiles. Besides a spike in prices between 2008 and 2009, average prices have remained relatively stable, though prices became more volatile toward the end of the sample. Electricity demanded experienced a small increase in the early years of the sample, after which it remained stable before experiencing a small decline in the latter years.

Figure 4 displays the evolution of the capacity price (red line), aggregate nameplate capaci-

¹⁰If the operator fails to reach a sufficient level of credit assignments, it can run a capacity auction for the remaining amount of desired capacity. Such an auction has never been necessary and therefore has never been run.

¹¹Capacity investment decisions are observed for most firms. For the facilities without capacity data, I infer capacities from quantities in the wholesale market. These imputed capacities are based on the maximum observed electricity produced in a half-hour interval by a generator. An analysis of the validity of these imputations can be found in Appendix E.1.

Figure 2: Energy Source Evolution over Time

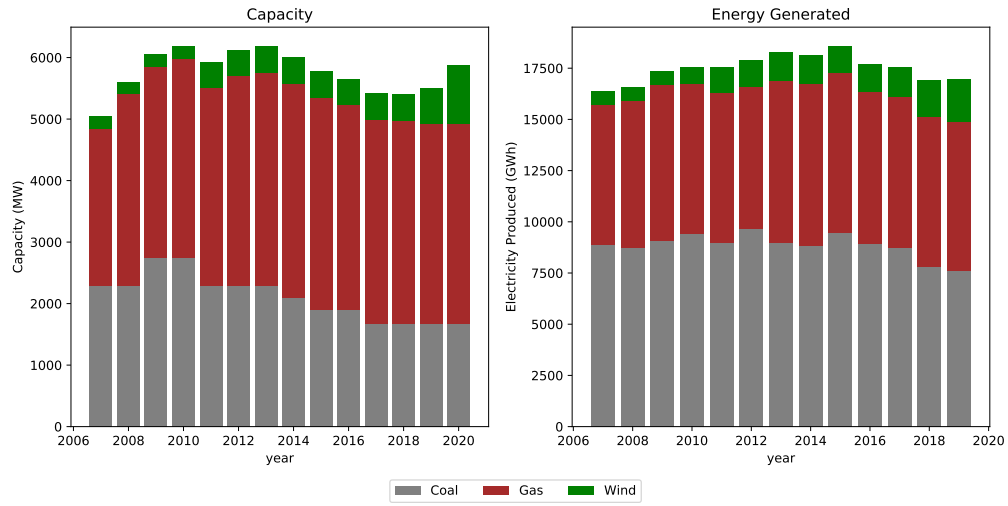


Figure 3: Prices and Quantities over Time

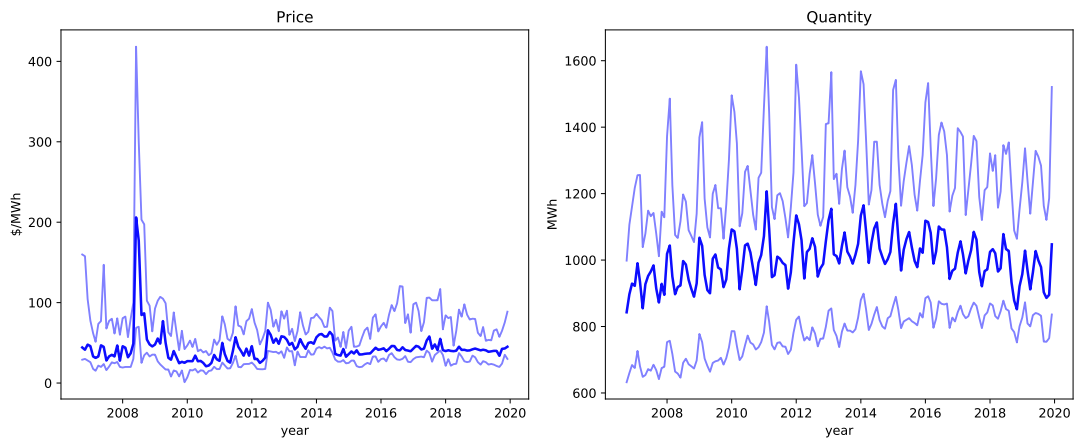


Table 1: Summary Statistics

	Mean	Std. Dev.	Min.	Max.	Num. Obs.
Half-hourly data					
Price	\$48.87	\$33.98	-\$68.03	\$498.0	258 576
Quantity (aggregate)	1 004.72	200.26	476.04	2 002.95	258 576
Quantity (firm-level)	3.92	29.57	0.0	859.04	66 195 456
Fraction capacity produced	0.26	0.29	0.0	1.0	66 195 456
Fraction capacity experiencing outage	0.06	0.23	0.0	1.0	4 137 216
Facility data					
Capacity	87.37	92.23	0.0	370.89	91
Capacity (coal)	161.83	79.17	58.15	341.51	17
Capacity (natural gas)	95.37	85.78	10.8	344.79	20
Capacity (wind)	59.42	75.54	0.95	206.53	16
Capacity price data					
Capacity price	\$130 725.56	\$24 025.49	\$97 834.89	\$186 001.04	14
Capacity commitments	54.57	229.64	0.0	3 350.6	1 274

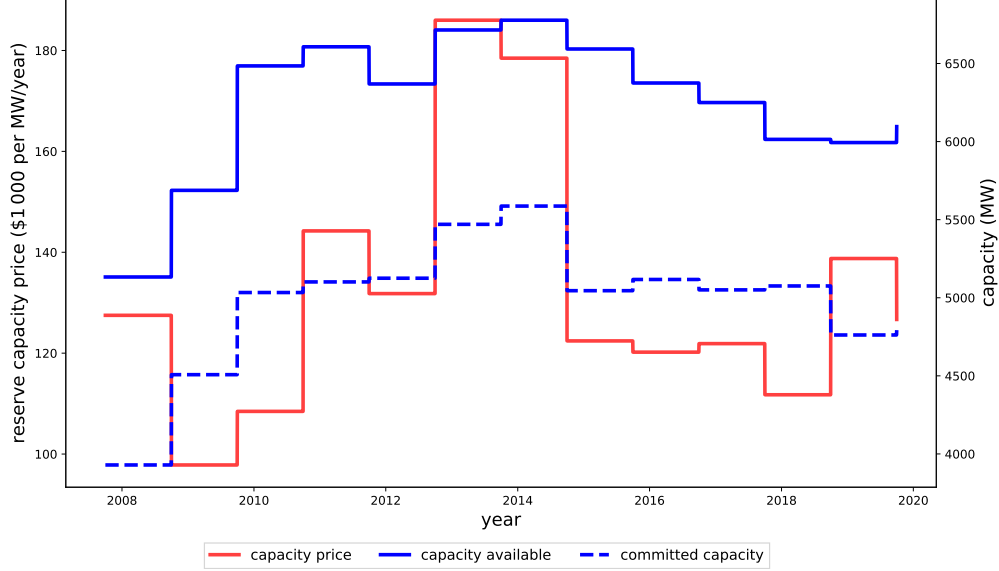
ties (blue solid line), and aggregate committed capacities (blue dashed line) over time. The capacity credit price mostly increased in the years leading up to 2014, after which it experienced a steep decrease before stabilizing. Both committed and nameplate capacities co-move with the capacity price. Each also increases in the years leading up to 2014, after which the market experiences net negative investment in capacity and lower levels of committed capacity. The correlation between the capacity price and the nameplate capacity is 0.516, and the correlation between the capacity price and the committed capacity is 0.551.

3 Model

In order to predict the impact of electricity market policies, I develop in this section a dynamic oligopolistic model of electricity production and investment in electricity generators. I combine a model of short-run wholesale electricity markets with a model of long-run investment. In the short-run wholesale market, firms use a fixed set of generators to produce electricity, and in the long-run, they can make costly adjustments to that set of generators. The short-run component of the model determines the returns to investment in a generator, and the long-run component models the trade-off firms make in that investment.

In the short-run wholesale market component, firms compete oligopolistically to supply a perfectly inelastic demand for electricity. This component provides the basis for the three market failures that characterize this market. First, the environmental externality is a result of the fact that generators emit greenhouse gases when they produce electricity. Second, the perfectly inelastic demand is a result of the lack of real-time pricing. Finally, firms have market power, creating a wedge between the private and social returns to production.

Figure 4: Capacity Price and Capacities



Over the long-run, firms make decisions whether to retire or add generators. These generators are then used in the wholesale market and carry over to future periods. The firms' investment decisions determine the level of investment, emissions, prices, and blackout frequencies. The investment decisions therefore determine the size of the welfare cost of the market failures in the wholesale market.

Before introducing each component of the model in detail, I will introduce some notation that is common to both components. I index firms by f . A firm can be either a part of a fixed set of strategic firms $\{1, \dots, n, \dots, N\}$ or belong to a competitive fringe c . The difference between the strategic firms and the competitive fringe is whether they take into account the impact their decisions have on the market price. The set of generators is given by \mathcal{G} . A generator $g \in \mathcal{G}$ varies in three ways: the firm to which it belongs, $f(g)$; its capacity, K_g ; and its energy source $s(g) \in \mathcal{S}$. Wholesale markets occur in intervals at the half-hourly level, indexed by h , and each interval h belongs to a year $t(h)$. Finally, the distribution of demand is given by \mathcal{Q} . Table 14 at the end of this paper provides a list of all parameters used in this section.

3.1 Short-run: Wholesale Market

Firms enter a wholesale market in interval h with a fixed set of generators $\mathcal{G}_{t(h)}$. At the beginning of the interval, several time-varying variables are realized: the effective capacities of each generator (after accounting for generator outages and intermittency in renewables),

the costs of producing electricity, and the demand for electricity. Firms then make static production decisions for each of their generators and compete in quantities (à la Cournot) to maximize their profits. Appendix B.1 provides a description of how this model of the wholesale market compares to other papers in the literature.

3.1.1 Model Primitives

The fractions of generators' capacities that are usable is given by δ_h . Generator $g \in \mathcal{G}_{t(h)}$ therefore has a maximum production capacity in interval h of $\bar{K}_{g,h} = \delta_{g,h} K_g$, where $\delta_{g,h} \in [0, 1]$. The effective capacity $\bar{K}_{g,h} \leq K_g$ reflects that generators cannot always produce at their nameplate capacities \mathbf{K} , which are the maximum levels of production possible under ideal circumstances. Generator outages occur for all types of generators. Moreover, intermittent renewables are constrained by the shining of the sun or the blowing of the wind and therefore sometimes can only produce at a fraction of their nameplate capacities.

Each generator g has a cost of producing $q_{g,h}$ Megawatt-hours of electricity, $c_{g,h}(q_{g,h})$. This cost reflects the purchase of inputs (such as natural gas for a gas generator), the efficiency of generation (which can vary, for example, with the temperature), and the fraction of a generator's capacity used. Generators also have a fixed cost, reflecting labor and other components that do not vary with the short-run quantity produced $q_{g,h}$. That cost is included in the long-run component of the model and does not affect the firms' short-run production decisions.

Explicitly, the cost function is given by

$$c_{g,h}(q_{g,h}) = \left(\zeta_{1,g,h} - \tau_{t(h)} r_{s(g)} \right) q_{g,h} + \zeta_{2,s(g)} \left(\frac{q_{g,h}}{K_g} \right)^2, \quad (1)$$

where $q_{g,h}$ is the amount of electricity produced by generator g in interval h . The linear parameter $\zeta_{1,g,h}$ reflects the component of marginal costs that are constant across quantities, such as the per-unit costs of coal or natural gas. It is generator- and time-varying because commodity prices vary over time and generators may face different costs or have different dynamic considerations not modeled here. The parameter τ_t is a carbon tax and r_s captures the rate of emissions per Megawatt-hour of electricity produced by a generator of source s .¹² The quadratic parameter $\zeta_{2,s}$ captures costs associated with using a large fraction of available capacity. I parameterize the linear parameter $\zeta_{1,g,h}$ by

$$\zeta_{1,g,h} = \mathbf{x}'_{g,h} \boldsymbol{\beta}_{s(g)} + \varepsilon_{g,h}, \quad (2)$$

¹²See Appendix A.4 for a list of these emissions rates.

where $\mathbf{x}_{g,h}$ is a vector of potentially generator- and time-varying covariates that affect the marginal cost of production, and $\varepsilon_{g,h}$ is a common-knowledge shock to marginal costs, possibly correlated with other such shocks.

The functional form chosen in equation 1 is influenced by, but differs in a key way from, other papers in the electricity literature estimating generator costs, primarily Wolak (2007) and Reguant (2014). Specifically, I follow the cost function of the cited papers in using a quadratic form, but equation 1 lacks the start-up and ramping costs that those papers incorporate. I have deliberately decided not to include these costs in order to keep the model of the wholesale market static. As discussed earlier, the decision to model the wholesale market as static allows me to tractably simulate the wholesale market an extremely large number of times in order to incorporate it into a larger model of generator investment. To the extent that there are dynamic costs not explicitly incorporated into this model, they will be absorbed in estimation into the distribution of ζ_1 . If, for example, demand rapidly increases, necessitating many firms to incur ramp-up costs, we will estimate a distribution of costs ζ_1 that have occasionally large shocks, correlated with one another, possibly correlated with demand. While concern over possible model misspecification remains, I believe that since start-up and ramping costs are invariant to the policies I consider in counterfactuals, and the estimated distribution carries over into the counterfactuals, this concern is partially alleviated.

Demand for electricity \bar{Q}_h is realized at the beginning of the interval, drawn from the distribution $\mathcal{Q}_{t(h)}$, which is exogenous in the short-run and potentially correlated with the other stochastic variables also realized in an interval h . Consumers do not pay the wholesale spot market prices and are therefore perfectly inelastic with respect to the short-run fluctuations in the wholesale price of electricity, so \bar{Q}_h does not respond to the wholesale market price. In equilibrium, conditional on there being sufficient capacity to satisfy demand, $\sum_{g \in \mathcal{G}_{t(h)}} q_{g,h} = \bar{Q}_h$. If, however, there is insufficient capacity, i.e., $\sum_{g \in \mathcal{G}_{t(h)}} \bar{K}_{g,h} < \bar{Q}_h$, a blackout results.

3.1.2 Firm Competition

Generators belong either to a strategic firm or to the competitive fringe. Generators in the competitive fringe take prices as given, yielding a generator supply curve given by

$$Q_{c,h}(P_h) = \sum_{g \in \mathcal{G}_{c,t(h)}} q_{g,h}^*(P_h),$$

where $q_{g,h}^*(P_h)$ for $g \in \mathcal{G}_{c,t(h)}$ is the quantity yielding a marginal cost of P_h (or the generator's constraints), i.e.

$$q_{g,h}^*(P_h) = \max \left\{ K_{s(g)}, \min \left\{ \bar{K}_{g,h}, \frac{P_h - \zeta_{1,g,h}}{2\zeta_{2,s(g)}/K_g^2} \right\} \right\},$$

where \bar{K}_g is the minimum production level of a generator of source s . Note that the second term in the minimum operator (the quantity yielding a marginal cost of P_h) comes from equation 1, the generator's cost function.

While consumers' demand for electricity in interval h is perfectly inelastic, strategic firms face a downward-sloping residual demand curve because generators belonging to the competitive fringe of producers respond to the market price. In equilibrium, demand equals supply. Whatever quantity strategic firms fail to supply will be made up by the competitive fringe, which determines the market price.

The inverse residual demand curve that the strategic firms face is therefore given by

$$P_h(Q_{s,h}) = Q_{c,h}^{-1}(\bar{Q}_h - Q_{s,h}), \quad (3)$$

where $Q_{s,h}$ is the quantity of electricity produced by the strategic firms.

Using equation 3, the profit function of a strategic firm $f \in \{1, \dots, N\}$ is

$$\pi_{f,h}(\mathbf{q}_{f,h}; \mathbf{q}_{-f,h}) = P_h(\mathbf{q}_h) \sum_{g \in \mathcal{G}_{f,t(h)}} q_{g,h} - \sum_{g \in \mathcal{G}_{f,t(h)}} c_{g,h}(q_{g,h}), \quad (4)$$

and the total profit of the competitive fringe is

$$\pi_{c,h}(\mathbf{q}_{s,h}) = P_h(\mathbf{q}_{s,h}) \sum_{g \in \mathcal{G}_{c,t(h)}} q_{g,h}^*(P_h(Q_{s,h})) - \sum_{g \in \mathcal{G}_{c,t(h)}} c_{g,h}(P_h(Q_{s,h})).$$

With the defined profit functions, the strategic firms play a Cournot game in quantities, constrained by the generators' constraints. Explicitly, for a strategic firm f ,

$$\mathbf{q}_{f,h}^*(\mathbf{q}_{-f,h}) = \arg \max_{\mathbf{K}_f \leq \mathbf{q}_{f,h} \leq \bar{\mathbf{K}}_{f,h}} \{\pi_{f,h}(\mathbf{q}_{f,h}, \mathbf{q}_{-f,h})\}. \quad (5)$$

These best response functions characterize the wholesale market equilibrium. The equilibrium quantities in h are given by the vector of strategic quantities $\mathbf{q}_{s,h}^*$ such that for each strategic firm f , $\mathbf{q}_{f,h}^* = \mathbf{q}_{f,h}^*(\mathbf{q}_{-f,h}^*)$. The quantities of the generators in the competitive fringe are given by $\mathbf{q}_{c,h}^*(P_h(Q_{s,h}^*))$. Appendix B.2 provides a detailed description of how to solve for \mathbf{q}_h^* .

Using the wholesale equilibrium quantities, we can define the correspondence mapping the set of generators to profits in the interval, $\pi_h : \Gamma \rightarrow \mathbb{R}^{N+1}$, where Γ is the set of all possible generator combinations, as

$$\pi_{f,h}(\mathcal{G}_t) = \pi_{f,h}(\mathbf{q}_h^*(\mathcal{G}_t)) \quad \forall f \in \{1, \dots, N, c\}. \quad (6)$$

3.2 Long-run: Generator Investment

Each year t , firms enter with a set of generators inherited from the previous year \mathcal{G}_{t-1} . The firms can choose to adjust their sets of generators by adding new ones and/or retiring existing generators. After (dis-)investment decisions are made, the newly updated set of generators, \mathcal{G}_t , is used in a series of many wholesale electricity markets, providing firms with a stream of profits. This chosen set of generators impacts the profits the firms receive—both through the changes induced by the choice in generators in cost and in competition—as well as the levels of emissions and the frequency of blackouts.

Investment decisions are dynamic and firms are strategic. The standard empirical model of oligopolistic industry dynamics is [Ericson & Pakes \(1995\)](#) (henceforth, EP), which is a stochastic dynamic game in which firms make simultaneous moves and face an infinite horizon. This model can yield multiple equilibria, coming from nonuniqueness of the stage game or through expectations over future values. While many papers have been able to analyze industry dynamics even in the presence of this multiplicity, this feature is particularly problematic for my setting. As will be discussed in more detail in the estimation section (section 4.2), data limitations prevent me from taking a non-parametric two-step estimator approach (such as [Bajari *et al.* \(2007\)](#)), as is common in the literature on estimating dynamic games.

In order to facilitate estimation through a maximum likelihood approach, as well as incorporate the non-stationarity of the cost of new generators (in particular wind), I define an equilibrium that removes both sources capable of generating multiple equilibria: the simultaneity of decisions and the infinite horizon. This modeling approach was developed and used by [Igami & Uetake \(2020\)](#) (henceforth, IU) in order to study endogenous mergers in the hard-drive disk industry. IU faced similar data limitations as I do and introduced to the EP framework sequential decisions within a period and a final period after which the game ends. I make similar modeling decisions as those in IU.¹³

¹³The exact modeling decisions of IU with respect to those two deviations from EP are as follows. First, for sequential decisions, they assume that one firm is selected to move in each period (each firm is strategic in their model). Second, for a final period, they assume that the value after a particular end date is 0 (because the hard-drive disk industry will cease to exist). I differ in the exact details with respect to both of these modeling decisions in order to fit my setting.

First, in each year one randomly-selected strategic firm will be allowed to adjust its set of generators, and all other strategic firms will keep their current sets of generators. This assumption is consistent with the data, in which at most one strategic firm adjusts its set of generators. After the strategic firm decides, the competitive fringe responds. With randomly chosen firms, I do not inherently bias the model in favor of a particular firm. Equilibria of sequential move games can be very different from their simultaneous move analogues in static settings.¹⁴

Second, I impose a finite horizon for the investment game in electricity generators. Specifically, I assume that in some final year, firms will cease to continue to be able to adjust their sets of generators. They will continue to receive profits from those generators for all eternity, but that game is a static one without dynamic considerations. This assumption allows firms to backward induct, yielding a unique equilibrium in investment decisions. The assumption of a year after which firms can no longer invest is a strong one; however, by choosing a date far in the future, I allow the industry to reach a steady state hopefully well-approximated by the repeated static game without investment. Additionally, I perform robustness checks, varying the date at which this occurs.

Beyond making a maximum likelihood estimator tractable, this definition of the investment game has some additional advantages that make it well-suited for considering investment in electricity generators. First, the game easily incorporates non-stationarity (and is, in fact, by definition non-stationary because there is a final end date). Many changes in electricity markets that I consider are non-stationary. The cost of new wind generators, for example, is non-stationary and has fallen precipitously over the course of the time period I consider. Any analysis of this markets must, therefore, incorporate this non-stationary. Additionally, the ability to solve the investment game via backward induction makes equilibrium computation relatively easy. This computational tractability allows me to consider a rich set of possible policies in order to determine optimal environmental and reliability policy.

With the aforementioned modeling assumptions, within-period timing is therefore as follows. Nature chooses a strategic firm to (potentially) make a costly adjustment to its set of generators. The competitive fringe observes this decision and responds. Firms then receive yearly profits as well as a capacity payments. The firms then all carry their generators over into the next period. In the last period of the game, firms can no longer adjust their sets of generators and must continue using them in all future periods.

¹⁴While one may worry that the introduction of random, sequential moves may bias the model in some significant way, [Doraszelski & Judd \(2019\)](#) find that in a quality ladder model they consider, the equilibria of dynamic games with random, sequential moves are “practically indistinguishable” from those of simultaneous moves (albeit in an infinite horizon setting).

3.2.1 Model Components

Conditional on a set of generators \mathcal{G}_t in the market, firms receive a stream of profits from the wholesale markets over the course of the year. The correspondence mapping \mathcal{G}_t to yearly expected profits, $\Pi_t : \Gamma \rightarrow \mathbb{R}^{N+1}$, is based on the wholesale profit correspondence π_h defined in equation 6, and is defined as

$$\Pi_{f,t}(\mathcal{G}_t) = \underbrace{\sum_h \mathbb{E}_{\bar{Q}_h(\bar{P}_t(\mathcal{G}_t)), \eta, \delta} [\pi_{f,h}(\mathcal{G}_t)]}_{\text{wholesale market profits}} - \underbrace{\sum_{g \in \mathcal{G}_{f,t}} M_{s(g)} K_g}_{\text{maintenance costs}} \quad \forall f \in \{1, \dots, N, c\}. \quad (7)$$

The first term of the above equation captures the total expected profits from the wholesale market over the year.¹⁵ The expectation is taken over demand shocks (\bar{Q}_t), cost shocks (ϵ), and production capacity shocks (δ), which all vary with h . The second term captures the cost of maintaining generators, where the cost for each generator is source-specific and in proportion to its capacity. This maintenance cost captures costs related to generators that are fixed with respect to the amount of electricity produced over the course of the year and therefore does not depend on generators' levels of production. This cost makes unused capacity costly.

While demand is perfectly inelastic in the short term, the distribution of inelastic demand shocks responds to the price level, which is captured in equation 7 by the dependency of \bar{Q}_t on the quantity-weighted average wholesale price \bar{P}_t . The details of this function can be found in Appendix B.3, which microfound electricity demand.

Since wholesale market prices depend on the set of generators in the market, the distribution of demand indirectly depends on the set of generators. The quantity-weighted average wholesale price \bar{P}_t is defined implicitly as a function of the generators \mathcal{G}_t as follows:

$$\bar{P}_t = \frac{\mathbb{E} [\bar{Q}_h(\bar{P}_t) P_h^*(\mathcal{G}_t)]}{\mathbb{E} [\bar{Q}_h(\bar{P}_t)]}, \quad (8)$$

where $P_h^*(\mathcal{G}_t)$ is the wholesale market price in interval h with the set of generators \mathcal{G}_t . Equation 8 requires that \bar{P}_t equals the quantity-weighted average wholesale price under the distribution of demand implied by \bar{P}_t . The long-run distribution of demand therefore responds to the set of generators in the market.

In addition to wholesale profits, firms can receive capacity payments over a year as a function of generator capacities. I model these payments based on the rules guiding the electricity

¹⁵Intervals take place every half-hour, and the summation is with respect to all intervals in a year, so there are 17 520 intervals.

market in Western Australia. The grid operator chooses a capacity credit price κ_t in year t . Each firm chooses a number of capacity credits to receive, modeled as the fraction of each of its generators' capacities to commit, γ_g . In each wholesale market, if a firm fails to have sufficient capacity to meet its commitment, then it must pay a penalty $\psi_{f,h}(\cdot)$. Such a penalty could occur due to an outage causing effective capacity $\bar{K}_{g,h}$ to fall below $\gamma_g K_g$, but *not* because the firm chooses to produce $q_{g,h}^* < \gamma_g K_g$.¹⁶

Over the year t , a firm f receives a net payment $\Upsilon_{f,t}(\cdot)$ based on its set of generators and the capacity credit price. Explicitly,

$$\Upsilon_{f,t}(\mathcal{G}_{f,t}; \kappa_t) = \max_{\gamma \in [0,1]^{G_{f,t}}} \left\{ \sum_{g \in \mathcal{G}_{f,t}} \gamma_g K_g \kappa_t - \mathbb{E} \left[\sum_h \psi_{f,h}(\gamma; \kappa_t, \mathcal{G}_{f,t}) \right] \right\}. \quad (9)$$

The first term captures the gross capacity payment (before paying any penalties). The second term captures the total penalty the firm expects to pay over the year. The function $\psi_{f,h}(\cdot)$ returns the penalty firm f must pay in interval h if it fails to have sufficient capacity to meet its obligation, defined as

$$\psi_{f,h}(\gamma; \kappa_t, \mathcal{G}_{f,t}) = \sum_{g \in \mathcal{G}_{f,t}} \lambda_{s(g)} \max \{ (\gamma_g - \delta_{g,h}) K_g, 0 \} \kappa_t,$$

where $\lambda_{s(g)}$ is a source-specific refund factor, which is multiplied by the committed capacity unavailable, scaled by the capacity price. A more detailed description of the capacity payment mechanism used by the WEM is given in Appendix A.

3.2.2 Strategic Firms

At the beginning of each year, a strategic firm $f \in \{1, \dots, N\}$ is randomly selected to adjust its set of generators. Each strategic firm has an equal probability of being selected, $\frac{1}{N}$. Firm f 's value function *prior to the strategic firm selection* is given by

$$W_{f,t}(\mathcal{G}_f; \mathcal{G}_{-f}, \mathcal{G}_c) = \sum_{m=1}^N \frac{1}{N} V_{f,t}^m(\mathcal{G}_f; \mathcal{G}_{-f}, \mathcal{G}_c), \quad (10)$$

where $V_{f,t}^m(\cdot)$ is firm f 's value function in the state of the world in which firm m is selected. If $m = f$, then the firm can adjust its own set of generators. Therefore, $V_{f,t}^f(\cdot)$ is the expected

¹⁶That the penalty depends on available *capacity* rather than *production* follows the capacity payment rules adopted by the WEM. Some electricity markets have adopted policies that more strongly incentivize production, such as that of Colombia, studied in detail by [McRae & Wolak \(2020\)](#). How to design capacity payments to incentivize efficient production is an interesting question that I do not examine in this paper, relying instead of the structure used by the WEM.

present-discounted value of firm f when it can optimally adjust its generators in the present year, other strategic firms cannot, and the competitive fringe responds. In the case where $m \neq f$, then a different firm can adjust its generators, and firm f remains with its current set. In this case, $V_{f,t}^m(\cdot)$ is the expected present-discounted value of firm f with its current set of generators, firm m optimally adjusting, other strategic firms keeping their current generators, and the competitive fringe responding.

The function $V_{f,t}^m(\cdot)$ is given formally below. A description of the function is given afterward.

$$V_{n,t}^m(\mathcal{G}_f; \mathcal{G}_{-f}, \mathcal{G}_c) = \begin{cases} \max_{\mathcal{G}'_f \in \Gamma_f} \left\{ \mathbb{E}_{\eta_c} \left[\Pi_{f,t}(\mathcal{G}'_f; \mathcal{G}_{-f}, \sigma_{c,t}(\mathcal{G}', \eta_c)) \right. \right. \\ \quad + \Upsilon_{f,t}(\mathcal{G}'_f; \kappa_t) \\ \quad - F \sum_s \mathbb{1} \{ \mathcal{G}'_{f,s} \neq \mathcal{G}_{f,s} \} \\ \quad - \sum_{g \in \mathcal{G}'_f} C_{s,t} K_g \mathbb{1} \{ g \notin \mathcal{G}_f \} \\ \quad + \eta_{f,\mathcal{G}'_f,t} \\ \quad \left. \left. + \beta \mathbb{E} \left[W_{f,t+1}(\mathcal{G}'_f; \mathcal{G}_{-f}, \sigma_c(\mathcal{G}', \eta_c)) \right] \right] \right\} & \text{if } m = f \\ \mathbb{E}_{\eta_{m,c}} \left[\Pi_{f,t}(\mathcal{G}_f; \mathcal{G}_{-f,-m}, \sigma_{m,t}(\mathcal{G}, \eta_m), \sigma_{c,t}(\mathcal{G}_{-m}, \sigma_{m,t}(\mathcal{G}, \eta_m), \eta_c)) \right. \\ \quad + \Upsilon_{f,t}(\mathcal{G}_f; \kappa_t) \\ \quad + \eta_{f,\mathcal{G}_f,t} \\ \quad \left. \left. + \beta \mathbb{E} [W_{f,t+1}(\mathcal{G}_f; \mathcal{G}_{-f,-m}, \sigma_{m,t}(\mathcal{G}, \eta_m), \sigma_{c,t}(\mathcal{G}_{-m}, \sigma_{m,t}(\mathcal{G}, \eta_m), \eta_c))] \right] \right\} & \text{if } m \neq f. \end{cases} \quad (11)$$

In the first case ($m = f$), firm f can adjust its generators. It can choose any set of generators in the set of possible sets of generators for the sources it uses, Γ_f . The firm then receives expected profits from the wholesale markets ($\Pi_{f,t}(\cdot)$), in which it is subject to its new, adjusted set of generators. While the other strategic firms do not adjust their generators, the competitive fringe can, so firm f takes an expectation over wholesale profits with respect to the competitive fringe's adjusted set of generators, given by $\sigma_{c,t}(\mathcal{G}', \eta_c)$. The second term is the net capacity payment that the firm receives with its adjusted set of generators. The third through fifth terms represent the adjustment cost. The third term is a fixed cost of adjustment that varies only by the number of energy sources adjusted, not the size of the adjustment. The fourth term captures the cost of building new generators, and scales with the size of an increase in capacity. The fifth term is an idiosyncratic cost shock and represents transmission line expansions, permitting, and land acquisition. The final term is the continuation value, carrying the set of generators over to the next period.

In the second case ($m \neq f$), firm f cannot adjust its generators. Its value in this period is therefore the sum of its expected wholesale profits (term 1), its net capacity payments (term 2), and its continuation value (term 3). Firm f takes an expectation over its wholesale profits

with respect to the adjustment of the adjusting firm (firm m) and the competitive fringe.

Note that the adjustment to the set of generators is immediate; when a firm adjusts its generators at the beginning of the year, it is able to use that adjusted capacity for all of the wholesale markets in that year. This timing assumption is motivated by when capacity prices are announced in Western Australia and how long it takes to build power plants. Capacity prices are announced three years prior to when they take effect (see Figure 1). The choice of three years notice is partially to give firms time to build new generators in response to the capacity price. While different energy sources take different amounts of time to build, three years is approximately sufficient for a firm to make adjustments. By allowing generators to come online in the same year that a capacity price goes into effect, I am capturing the effect of pre-announced capacity prices and time-to-build.¹⁷

3.2.3 Competitive Fringe

The competitive fringe enters a year observing the *adjusted* set of generators of the strategic firms from the earlier stage \mathcal{G}_{-c} .¹⁸ The competitive fringe is made up of many generators that make separate entry decisions. Generators that have not entered may choose to enter or to remain out of the market and wait to potentially enter in a future period. Generators that have already entered may choose to remain in the market or to retire the generator. After retirement, a generator may re-enter, but it must pay the investment cost again.¹⁹

A competitive generator g 's value function is given below. The value function is denoted by $v_{g,t}(\cdot)$, where the lower script denotes that it is a competitive single generator (rather than one of the strategic firms with multiple generators, which use an upper case V). The function takes as arguments whether a generator has already entered the market (given by $e \in \{\text{in}, \text{out}\}$), as well as the set of competitive and strategic generators *before* competitive

¹⁷A slightly more realistic model may have a state space that keeps track of this year's capacity price as well as the next three, as well as this year's generators and those that will come online in the next few years. I do not adopt this modeling choice because it would be computationally intractable to use such a large state space. I do not believe that differences in time-to-build across different technologies will have a meaningful impact on the results.

¹⁸Note that this vector may be different from the set of generators the strategic firms observe when they make decisions. If a firm chooses to adjust, then the set of generators *after adjustment* is what the competitive fringe observes.

¹⁹The decision to allow generators to re-enter is made to match the modeling of strategic firms, which can retire a generator and then build it anew. Since investment costs are substantial and maintenance costs do not fluctuate over time, this modeling assumption should not ultimately matter. While any such investment decision has positive probability (since the idiosyncratic shocks have full support along the real line), there is no strong incentive to retire a generator and then build it again.

generators make entry decisions in this period.

$$v_{g,t}(e, \mathcal{G}_c, \mathcal{G}_s) = \begin{cases} \max_{\text{in / out}} \left\{ \begin{aligned} &\Pi_{g,t}(\mathcal{G}_t^*(\mathcal{G}, \boldsymbol{\eta}_c)) \\ &+ \Upsilon_{g,t}(\{g\}; \kappa_t) \\ &- C_{s(g),t} K_g \\ &+ \eta_{g,e,t} \\ &+ \beta \mathbb{E}_{\boldsymbol{\eta}_{-c}} \left[\frac{1}{N} \sum_{m=1}^N v_{g,t+1} \left(\text{in}, \mathcal{G}_{c,t}^*(\mathcal{G}, \boldsymbol{\eta}_c), \mathcal{G}_{-c,-m}, \sigma_{m,t+1}(\mathcal{G}_t^*(\mathcal{G}), \boldsymbol{\eta}_m) \right) \right], \\ &\eta_{g,e,t} \\ &+ \beta \mathbb{E}_{\boldsymbol{\eta}_{-c}} \left[\frac{1}{N} \sum_{m=1}^N v_{g,t+1} \left(\text{out}, \mathcal{G}_{c,t}^*(\mathcal{G}, \boldsymbol{\eta}_c), \mathcal{G}_{-c,-m}, \sigma_{m,t+1}(\mathcal{G}_t^*(\mathcal{G}), \boldsymbol{\eta}_m) \right) \right] \end{aligned} \right\} & \text{if } e = \text{out} \\ \max_{\text{in / out}} \left\{ \begin{aligned} &\Pi_{g,t}(\mathcal{G}_t^*(\mathcal{G}, \boldsymbol{\eta}_c)) \\ &+ \Upsilon_{g,t}(\{g\}; \kappa_t) \\ &+ \eta_{g,e,t} \\ &+ \beta \mathbb{E}_{\boldsymbol{\eta}_{-c}} \left[\frac{1}{N} \sum_{m=1}^N v_{g,t+1} \left(\text{in}, \mathcal{G}_{c,t}^*(\mathcal{G}, \boldsymbol{\eta}_c), \mathcal{G}_{-c,-m}, \sigma_{m,t+1}(\mathcal{G}_t^*(\mathcal{G}), \boldsymbol{\eta}_m) \right) \right], \\ &\eta_{g,e,t} \\ &+ \beta \mathbb{E}_{\boldsymbol{\eta}_{-c}} \left[\frac{1}{N} \sum_{m=1}^N v_{g,t+1} \left(\text{out}, \mathcal{G}_{c,t}^*(\mathcal{G}, \boldsymbol{\eta}_c), \mathcal{G}_{-c,-m}, \sigma_{m,t+1}(\mathcal{G}_t^*(\mathcal{G}), \boldsymbol{\eta}_m) \right) \right] \end{aligned} \right\} & \text{if } e = \text{in}. \end{cases} \quad (12)$$

A generator enters a year t as either not having already entered the market (the first case in equation 12) or having entered it (the second case). If it has not entered the market, then it can either pay the cost of investment (analogous to that of strategic firms) and enter the market (receiving wholesale profits and capacity payments), or it can not enter and potentially enter in a future year. If the generator has already entered the market, it can either continue existing, and receive profits and capacity payments, or it can retire (but potentially re-enter in a future year).

The generator set $\mathcal{G}_t^*(\cdot)$ is the equilibrium set of competitive generators in year t . It takes as an input the set of strategic generators (after making adjustment decisions in that year) and the incumbent competitive generators. This set is determined by a free entry condition: generators enter (or retire) up to the point that profits are zero. Appendix C.5 includes more details about how this set is determined.

3.2.4 Final Period of Adjustment

Firms adjust their sets of generators for the final time in year T . In all periods $t > T$, firms continue to compete in wholesale electricity markets with the set of generators \mathcal{G}_T chosen in year T . This is simply a static game repeated over time. Therefore, the value in year $T + 1$

is given by

$$V_{f,T+1}(\mathcal{G}_f; \mathcal{G}_{-f}) = \sum_{t=T+1}^{\infty} \beta^{t-T-1} \mathbb{E} \left[\Pi_{f,t}(\mathcal{G}_f; \mathcal{G}_{-f}) + \Upsilon_{f,t}(\mathcal{G}_f; \kappa_t) + \eta_{f,\mathcal{G}_f,t} \right]. \quad (13)$$

Given the final period defined above, I can solve for the (unique) equilibrium of this game using backward induction.

4 Estimation and Identification

In the following section I develop a method for estimating the model described in section 3. I estimate this model in two stages. In a first stage I estimate the parameters governing the wholesale market, including production costs and the distribution of demand. I then use these first-stage estimates to construct the expected yearly profit function (equation 7), which I use to estimate the parameters governing firms' investment decisions, including the sunk costs of investment and fixed maintenance costs. I specify the three largest firms in the market (measured both in capacities as well as electricity supplied) as the strategic firms and assume that all other generators belong to the competitive fringe. These three firms are substantially larger than the next largest firm, creating a natural cutoff point between strategic firms and the fringe.

4.1 Wholesale Market Estimation

In the first stage, I need to estimate the joint distribution of generator costs, capacity factors, and demand shocks. Capacity factors and demand are both observed in the data. I recover capacity factors using detailed outage data provided by the grid operator that reports the size of outages for each generator. Short-run demand is perfectly inelastic, and therefore the quantity of electricity provided in a given interval is simply the quantity supplied by generators during that time, which is observed (conditional on no blackouts occurring, which is an extremely rare event).²⁰

Generator costs, in contrast, are not directly observed in the data. For each generator, I observe the quantity of electricity produced, but not the cost of producing it. I can, however,

²⁰Like many electricity markets, there do exist so-called demand-response participants, which participate in the wholesale market auctions with a bid to *decrease consumption*. While their existence means that demand is not truly *perfectly* inelastic, the reduction in demand from these participants constitutes an extremely small fraction of total market demand [NEED THE NUMBER, BUT I KNOW IT'S TINY], and I therefore ignore them.

use the firms' first order conditions associated with equation 5 to recover marginal costs. The model provides an inversion between the prices and quantities observed and unconstrained generators' marginal costs. Generators, however, frequently produce zero electricity or their full capacity. For generators that are constrained in an interval at either their lower production limit \underline{K}_g or their upper one $\bar{K}_{g,h}$, the first order conditions do not hold exactly but do imply a bound on marginal costs. I use both the recovered marginal costs as well as those bounds to estimate the distribution of marginal costs via maximum likelihood with a Tobit likelihood.

Separate identification of the component of cost that depends on the fraction of capacity used (ζ_2) from the constant component (ζ_1) comes from the covariance between price and capacity utilizations (i.e., the fraction of capacity used). If capacity utilizations and prices are highly positively correlated (capacity utilizations are high when prices are high, and they are low when prices are low), ζ_2 is large relative to the variance of the cost shocks ε . If it is expensive to use a large fraction of capacity (high ζ_2), then when \bar{Q}_h is high, necessitating a high capacity utilization, prices will rise. If, in contrast, capacity utilizations and prices are weakly correlated, then ζ_2 is small relative to the variance of the cost shocks. In that case, most of the difference in costs comes from shocks to ζ_1 , and high prices come from expensive generators needing to run rather than needing to use high fractions of generators' capacities. This correlation determines the relative scale of these parameters to one another, and the level is determined by the range of prices observed.

The identification argument described above is nonparametric, but I impose a parametric distribution on the cost shocks ε for the sake of tractability. Specifically, I assume that

$$\varepsilon_h \sim \mathcal{N}(\mathbf{0}, \Sigma_\varepsilon).$$

There are two ways in which this parametric distribution makes estimation more tractable, both related to allowing correlation among generators' cost shocks within an interval. It is important to allow for this correlation since it impacts the profits firms expect when they choose to add or retire generators.²¹ First, the Tobit likelihood combines the unconstrained generators' cost shocks likelihood with the likelihood that the constrained generators' cost shocks exceed some bounds. With correlation among cost shocks, as I explain in the following section, we must condition the constrained generators' likelihood on the unconstrained cost shocks. Generally speaking, solving for the conditional probability $F(X_2|X_1 = x_1)$ of an arbitrary distribution F can be difficult, but the conditional distribution of a multivariate normal is a multivariate normal, making computation relatively easy. Second, with many generators, the dependence among cost shocks is extremely high-dimensional, requiring an

²¹Indeed, I find that the correlation across generators' cost shocks is very high (see table 2 in section 5).

enormous data requirement beyond even the hundreds of thousands of wholesale markets I observe. The multivariate normal puts structure on the correlation, which reduces the dimension of the object I estimate, thereby making the estimation problem tractable.

4.1.1 Generator Costs

Generators' costs are specified in equation 1, provided again below for convenience:

$$c_{g,h}(q_{g,h}) = \left(\zeta_{1,g,h} - \tau_{t(h)} r_{s(g)} \right) q_{g,h} + \zeta_{2,s(g)} \left(\frac{q_{g,h}}{K_g} \right)^2, \quad (1 \text{ revisited})$$

where

$$\zeta_{1,g,h} = \mathbf{x}'_{g,h} \boldsymbol{\beta}_{s(g)} + \varepsilon_{g,h}. \quad (2 \text{ revisited})$$

Wind generators have zero marginal costs, so I do not need to estimate the distribution of wind generators' costs. I use $\tilde{\mathcal{G}}$ to denote only the set of thermal generators (i.e., coal and gas generators, excluding wind). I further partition the set of generators by whether or not the generator is (optimally) operating at a constraint in a given interval h based on the quantity $q_{g,h}$ I observe in the data. Let $\tilde{\mathcal{G}}_h^u$ denote the set of generators unconstrained in interval h , i.e., $q_{g,h} \in (\underline{K}_{s(g)}, \bar{K}_{g,h})$; $\tilde{\mathcal{G}}_h^-$ the generators constrained from below, i.e., $q_{g,h} \leq \underline{K}_g$; and $\tilde{\mathcal{G}}_h^+$ the generators constrained from above, i.e., $q_{g,h} = \bar{K}_{g,h}$.²² The set $\tilde{\mathcal{G}}_h^{-u} = \tilde{\mathcal{G}}_h^- \cup \tilde{\mathcal{G}}_h^+$ will denote those that are constrained from any direction. Superscripts on generator-level variables (such as \mathbf{q} or ε) will similarly denote the subset of that variable for which the corresponding generators belong to the set of thermal generators with the same superscript (e.g., \mathbf{q}_h^+ is the quantities in interval h produced by the generators in $\tilde{\mathcal{G}}_h^+$).

Unconstrained Generators The idea behind the estimation procedure is to use the generators' production first order conditions associated with equation 5, given below, to back out the distribution of costs:

$$\begin{aligned} P_h &= \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{q_{g,h}}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{c,h}^u \\ MR_{g,h} &= \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{q_{g,h}}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{s,h}^u. \end{aligned} \quad (14)$$

Note that the marginal revenue of strategic generators, $MR_{g,h}$, is a function of the competitive supply curve and the other strategic firms' production decisions.

²²The relation between $q_{g,h}$ and \underline{K}_g is an inequality rather than an equality because \underline{K}_g is not necessarily zero. Coal generators, for example, have a minimum production level of approximately $\frac{1}{2}K_g$. If a generator fails to produce at least \underline{K}_g , then it simply shuts down and produces 0.

Since $q_{g,h}$ is a function of each generator's cost shock $\varepsilon_{g,h}$, I cannot solve for ε_h^u by simply subtracting the first two terms on the right hand side of equation 14 from the left hand side. While this would yield ε_h^u at the true cost parameters (β, ζ_2) , solving for ε_h^u in this way will lead to an inconsistent estimator for these parameters. This is due to endogeneity because \mathbf{q}_h^u is a function of ε_h^u .

Instead, I solve for the equilibrium prices and quantities as a function of the cost shocks, and then invert the observed prices and quantities to obtain the cost shocks, accounting for the endogeneity of \mathbf{q}_h^+ . The first order conditions in equation 14 provide this mapping from ε_h^u to (\mathbf{q}_h^u, P_h) . Appendix C.2 provides a closed form solution to this system of equations (equations 40 and 41) and shows that it is an injective correspondence. I denote this correspondence by $\phi_h(\cdot)$. Because $\phi_h(\cdot)$ is injective, it is invertible, and Appendix C.2 provides a closed form (equation 42) of the inversion from (\mathbf{q}_h^u, P_h) to ε_h^u , $\phi_h^{-1}(\cdot)$.

Conditional on the cost parameters (β, ζ_2) , I can therefore recover the unconstrained cost shocks as follows:

$$\varepsilon_h^u(\beta, \zeta_2) = \phi_h^{-1}(\mathbf{q}_h^u, P_h; \beta, \zeta_2).$$

Constrained Generators The above method recovers the cost shocks for $g \in \tilde{\mathcal{G}}_h^u$, and I now describe how I bound the cost shocks for $g \in \tilde{\mathcal{G}}_h^{-u}$. As with the unconstrained generators, the first order conditions in equation 14 provide information relevant to the realizations of ε_h . I can replace the equalities in equation 14 with inequalities, as follows:²³

$$\begin{aligned} P_h &\leq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_g}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{c,h}^- \\ P_h &\geq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_{g,h}}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{c,h}^+ \\ MR_{g,h} &\leq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_g}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{s,h}^- \\ MR_{g,h} &\geq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_{g,h}}{K_g^2} + \varepsilon_{g,h} & \forall g \in \tilde{\mathcal{G}}_{s,h}^+. \end{aligned} \tag{15}$$

Unlike with in equation 14 for the unconstrained generators, \mathbf{q}_h^{-u} does not enter the right hand side of the inequalities in equation 15. I therefore do not have the same endogeneity problem with the quantities, and the inversion is therefore easier. I can simply subtract the first two terms of the right hand side of each inequality from the left hand side and obtain bounds on ε_h^{-u} .

In order to construct these bounds, I must determine the marginal revenue for the strategic, constrained generators. The marginal revenue is a function of the residual demand that the strategic firms face, which is the competitive supply subtracted from the market demand. Us-

²³I am using here that $\zeta_{2,s} > 0$ for all s .

ing $\varepsilon_h^u(\beta, \zeta_2)$, we can trace out locally the supply curve for competitive firms, which Appendix B.2 shows is linear:

$$Q_{c,h}(P_h; \beta, \zeta_2) = \underbrace{\sum_{g \in \mathcal{G}_{c,h}^+} \bar{K}_{g,h}}_{\text{constrained generators}} + \underbrace{\alpha_h(\varepsilon_h^u(\beta, \zeta_2)) + \beta_h(\varepsilon_h^u(\beta, \zeta_2)) P_h}_{\text{unconstrained generators}}.$$

Note that the supply curve here is the *local* supply curve. As P_h increases, generators' capacity constraints will bind and the constraints of generators constrained from below will cease to bind, giving me a different (but still linear) function. I am only interested in the supply function in order to construct strategic generators' marginal revenues at the quantity $\mathbf{q}_{s,h}$ observed in the data, however. The local supply curve is all that matters for this calculation. Therefore, to calculate strategic generators' marginal revenues at $\mathbf{q}_{s,h}$, I can ignore the fact that competitive generators' capacity constraints will bind (or cease to) at points outside of a neighborhood around $\mathbf{q}_{s,h}$.

The residual demand curve that the strategic firms face is therefore

$$P_h(\mathbf{q}_h; \beta, \zeta_2) = \frac{\bar{Q}_h - Q_h^{\text{wind}} - \sum_{g \in \mathcal{G}_{c,h}^+} \bar{K}_{g,h} - \alpha_h(\varepsilon_h^u(\beta, \zeta_2)) - \sum_{g \in \mathcal{G}_s} q_{g,h}}{\beta_h(\varepsilon_h^u(\beta, \zeta_2))},$$

which we can rewrite as

$$P_h(\mathbf{q}_{s,h}; \beta, \zeta_2) = a_h(\beta, \zeta_2) - b_h(\beta, \zeta_2) \sum_{g \in \mathcal{G}_s} q_{g,h}.$$

The marginal revenue $MR_{g,h}$ for the strategic generators is therefore given by

$$MR_{g,h}(\beta, \zeta_2) = a_h(\beta, \zeta_2) - b_h(\beta, \zeta_2) \sum_{\substack{g' \in \tilde{\mathcal{G}}_s: \\ f(g') \neq f(g)}} q_{g',h} - 2b_h(\beta, \zeta_2) \sum_{\substack{g' \in \tilde{\mathcal{G}}_s: \\ f(g') = f(g)}} q_{g',h}.$$

Likelihood With the ability to back out the cost shocks for unconstrained generators and bounds for the constrained ones, I can construct a Tobit-like estimator that combines the density function of ε_h with the c.d.f. to estimate the model's parameters. With a univariate Tobit, each draw is independent, so we do not need to condition one draw on another's outcome. In my case, I have dependent cost draws across generators within an interval, meaning that the cost shock realization I back out for unconstrained generators is informative about the likelihood of the realizations I cannot back out and must bound. In order to calculate the joint likelihood in an interval, which I denote $\tilde{f}_h(\cdot)$, I break the likelihood into

the marginal density of the unconstrained generators and the conditional probability of the constrained firms:

$$\tilde{f}_h(\varepsilon_h) = f_h(\varepsilon_h^u) F_h(\varepsilon_h^{-u} | \varepsilon_h^u).$$

I use this likelihood function to estimate the cost distribution parameters via maximum likelihood.

As discussed earlier, I assume that the generator cost shocks are jointly realized in each interval (allowing for correlation) and are normally distributed $\varepsilon_h \sim \mathcal{N}(\mathbf{0}, \Sigma_\varepsilon)$, where Σ_ε is the covariance matrix, given by

$$\Sigma_\varepsilon = \begin{bmatrix} \sigma_1^2 & \rho_{1,2}\sigma_1\sigma_2 & \dots & \rho_{1,G}\sigma_1\sigma_G \\ \rho_{2,1}\sigma_2\sigma_1 & \sigma_2^2 & & \\ \vdots & & \ddots & \\ \rho_{G,1}\sigma_G\sigma_1 & & & \sigma_G^2 \end{bmatrix}.$$

Values vary only at the energy source-level (*i.e.*, $\sigma_g = \sigma_{s(g)}$, $\rho_{g,g'} = \rho_{s(g),s(g')}$). The value $\rho_{s,s'}$ captures the correlation between energy sources s and s' . This restriction reduces the number of correlation parameters we need to estimate and makes likelihood computations much simpler.

For notational convenience, I combine both competitive and strategic generator inversions implied by equation 15. Let

$$\nu_{g,h}(\beta, \zeta_2) = \begin{cases} P_h - \beta'_{s(g)} \mathbf{x}_{g,h} - 2\zeta_{2,s(g)} \frac{q_{g,h}}{K_g^2} & \text{if } g \in \mathcal{G}_c \\ MR_{g,h}(\beta, \zeta_2) - \beta'_{s(g)} \mathbf{x}_{g,h} - 2\zeta_{2,s(g)} \frac{q_{g,h}}{K_g^2} & \text{if } g \in \mathcal{G}_s. \end{cases}$$

The log-likelihood of observations is given by²⁴

$$\begin{aligned} \ell(\beta, \zeta_2, \Sigma_\varepsilon) &= \sum_h \log \left(\phi_{G_h^u}(\varepsilon_h^u(\beta, \zeta_2); \Sigma_\varepsilon) \right) \\ &\quad + \log \left(\Pr \left(\varepsilon_h^+ \leq \nu_h^+(\beta, \zeta_2) \text{ and } \varepsilon_h^- \geq \nu_h^-(\beta, \zeta_2) \middle| \varepsilon_h^u = \varepsilon_h^u(\beta, \zeta_2); \Sigma_\varepsilon \right) \right). \end{aligned} \tag{16}$$

4.1.2 Other Wholesale Market Parameters

In addition to cost shocks, each interval in the wholesale market contains demand shocks \bar{Q}_h and effective capacity shocks δ_h . I assume that demand shocks are log-normally distributed and allow for these shocks to be correlated with the available wind capacity.

²⁴See Appendix C.3 for details on computing the second term in equation 16.

Wind capacity factors δ_h^{wind} lie in the interval $(0, 1)^{G_{\text{wind},h}}$. I flexibly capture correlation among these nonzero capacity factor shocks and with demand shocks by assuming that a random variable \mathbf{x}_h is drawn from a multivariate normal distribution, and $\delta_{g,h} = f(x_{g,h})$, where $f : \mathbb{R} \rightarrow (0, 1)$ is the standard logistic function $f(x) = \frac{\exp(x)}{1 + \exp(x)}$.

Explicity, I denote the joint vector of transformed demand shocks and wind capacity factors as $\boldsymbol{\omega}_h$, which is distributed

$$\underbrace{\begin{bmatrix} \log(\bar{Q}_h) \\ \log\left(\frac{\delta_h^{\text{wind}}}{1 - \delta_h^{\text{wind}}}\right) \end{bmatrix}}_{=:\boldsymbol{\omega}_h} \sim \mathcal{N}(\boldsymbol{\mu}_\omega, \boldsymbol{\Sigma}_\omega). \quad (17)$$

The correlation matrix $\boldsymbol{\Sigma}_\omega$ is given by

$$\boldsymbol{\Sigma}_\omega = \begin{bmatrix} \sigma_{\bar{Q}}^2 & \rho_{\bar{Q},\delta} \sigma_{\bar{Q}} \sigma_\delta & \cdots & \rho_{\bar{Q},\delta} \sigma_{\bar{Q}} \sigma_\delta \\ \rho_{\bar{Q},\delta} \sigma_{\bar{Q}} \sigma_\delta & \sigma_\delta^2 & \cdots & \rho_{\delta,\delta} \sigma_\delta^2 \\ \vdots & \vdots & \ddots & \\ \rho_{\bar{Q},\delta} \sigma_\delta \sigma_{\bar{Q}} & \rho_{\delta,\delta} \sigma_\delta^2 & \cdots & \sigma_\delta^2 \end{bmatrix}.$$

The correlation parameters $\rho_{\bar{Q},\delta}$ and $\rho_{\delta,\delta}$ capture the correlation between demand shocks and wind capacity factors and within capacity factors, respectively.

Coal and gas capacity factors have a different support than do wind capacity factors. Unlike wind, for which capacity factors capture the extent to which the wind blows, coal and gas capacity factors capture whether a generator is experiencing an outage. These factors therefore have the support $\{0, 1\}$. I assume that δ_h^{wind} are independent and distributed as follows. For each $g \in \tilde{\mathcal{G}}$,

$$\delta_{g,h} = \begin{cases} 1 & \text{with probability } p_{s(g)} \\ 0 & \text{with probability } 1 - p_{s(g)}. \end{cases}$$

Cost shocks, demand shocks and wind capacity factors, and thermal generator capacity factors

are independent across these groups.²⁵ The log-likelihood function therefore is given by

$$\begin{aligned} \ell(\beta, \zeta_2, \Sigma_\varepsilon, \mu_\omega, \Sigma_\omega, \mathbf{p}) &= \sum_h \log \left(\phi_{G_h^u}(\varepsilon_h^u(\beta, \zeta_2); \Sigma_\varepsilon) \right) \\ &\quad + \log \left(\Pr \left(\varepsilon_h^+ \leq \nu_h^+(\beta, \zeta_2) \text{ and } \varepsilon_h^- \geq \nu_h^-(\beta, \zeta_2) \middle| \varepsilon_h^u = \varepsilon_h^u(\beta, \zeta_2); \Sigma_\varepsilon \right) \right) \\ &\quad + \log \left(\phi(\omega_h; \mu_\omega \Sigma_\omega) \right) \\ &\quad + \sum_{g \in \tilde{\mathcal{G}}} \left(\delta_{g,h} \log(p_{s(g)}) + (1 - \delta_{g,h}) \log(1 - p_{s(g)}) \right). \end{aligned} \tag{18}$$

The first line captures the likelihood of the unconstrained cost shocks and the second line the constrained cost shocks. The third line captures the likelihood of the demand shocks and wind capacity factors. Finally, the last line captures the likelihood of the thermal generator capacity factors.

I can therefore estimate the cost distribution via maximum likelihood:

$$\hat{\beta}, \hat{\zeta}_2, \hat{\Sigma}_\varepsilon, \hat{\mu}_\omega, \hat{\Sigma}_\omega, \hat{\mathbf{p}} = \arg \max \{ \ell(\beta, \zeta_2, \Sigma_\varepsilon, \mu_\omega, \Sigma_\omega, \mathbf{p}) \}.$$

4.2 Investment Decision Estimation

With the cost and demand distributions estimated as described in section 4.1, the remaining parameters of the model are those that enter the long-run stage of the model. These include maintenance costs $\{M_s\}_{s \in \mathcal{S}}$, the fixed cost of investment F , the variable cost of investment $\{C_{s,t}\}_{s,t}$, the distribution of the idiosyncratic shocks ε , and the discount factor β . As is common in the discrete choice literature, I assume that the idiosyncratic shocks are Type I Extreme Value, yielding closed form choice probabilities. Estimating the distribution of the idiosyncratic shocks thus reduces to estimating the variance of these shocks. Following Igami & Uetake (2020), I use a full-information maximum likelihood approach to estimate these parameters. The full-information approach, in which I compute the equilibrium of the model for every guess of the parameters is feasible because the equilibrium is unique and relatively simple to compute using backward induction. Moreover, this method allows me to incorporate nonstationary investment costs and provides precise estimates because it uses the full structure of the model. The latter point is important because I have limited data corresponding to investment (only 14 years and a single market), making the precision of the estimates a primary concern. The approaches common in the dynamic games estimation literature, which are two-step procedures, would therefore be infeasible in this setting.²⁶

²⁵In theory, I could also allow for correlation across these groups of shocks. In practice, to reduce the dimension of the parameter space, I assume that these groups are independent. Demand shocks and thermal generator capacity factors, both of which I observe, are virtually uncorrelated in the data.

²⁶These procedures include Bajari *et al.* (2007); Pakes *et al.* (2007); Aguirregabiria & Mira (2007); Pensorfer & Schmidt-Dengler (2008).

Since the variable cost component of investment is non-stationary and I observe only one market, it is infeasible to estimate these time-varying costs. Instead, I use engineering estimates to construct the path of new generator costs in each year for each energy source.²⁷ I assume that firms have perfect foresight over the path of future generator costs. Since there is no uncertainty in future costs, generator costs are simply included in the time dimension of the state.

Typically in dynamic discrete choice models, the discount factor is not identified. [Magnac & Thesmar \(2002\)](#) show that identification relies on exclusion restrictions that vary either the present value or the expected future value, but not the other. Since future generator costs and future capacity prices vary the returns to investment in future years *but not the present year*, this exclusion restriction is satisfied. The model is thus identified, and I estimate the discount factor in addition to the dynamic costs.

The likelihood function for a firm f in year t implied by the model is given by

$$\mathcal{L}_{f,t}(\boldsymbol{\theta}) = \Pr(f \in \chi_t; \mathcal{G}_t, \mathcal{G}_{t-1}) \times \prod_{\mathcal{G}' \in \Gamma_f} \Pr(\mathcal{G}' = \mathcal{G}_{f,t} | \mathcal{G}_{-f,t}, \mathcal{G}_{t-1}, t)^{\mathbf{1}_{\{\mathcal{G}' = \mathcal{G}_{f,t}\}}}, \quad (19)$$

where χ_t is the set of firms selected to move in year t . I can determine $\Pr(f \in \chi_t)$ based on generator investment decisions. If a strategic firm adjusts its set of generators in one year, then it must be the case that it was the firm selected to adjust, and this probability is zero for all other firms. Note that it is never the case in the sample that multiple strategic firms adjusted their generators in the same years. This probability is therefore

$$\Pr(f \in \chi_t; \mathcal{G}_t, \mathcal{G}_{t-1}) = \begin{cases} 1 & \text{if } f = c \\ 1 & \text{if } f \neq c \text{ and } \mathcal{G}_{f,t} \neq \mathcal{G}_{f,t-1} \\ 0 & \text{if } f \neq c \text{ and } \exists f' \in \{1, \dots, N\} \setminus \{f\} \text{ s.t. } \mathcal{G}_{f',t} \neq \mathcal{G}_{f',t-1} \\ \frac{1}{N} & \text{if } f \neq c \text{ and } \forall f' \in \{1, \dots, N\}, \mathcal{G}_{f',t} = \mathcal{G}_{f',t-1}. \end{cases}$$

The maximum likelihood estimator is therefore given by

$$\hat{\boldsymbol{\theta}}(\mathcal{G}) = \arg \max_{\boldsymbol{\theta} \in \Theta} \left\{ \frac{1}{2} \frac{1}{T_{obs}} \sum_{t=1}^{T_{obs}} \log \left(\sum_f \mathcal{L}_{i,t}(\boldsymbol{\theta}) \right) \right\}, \quad (20)$$

where T_{obs} is the number of observed periods. Note that in taking the average log-likelihood, I multiply by $\frac{1}{2}$ rather than $\frac{1}{N+1}$ (where $N+1$ is the number of firms plus the competitive fringe).

²⁷Specifically, I use engineering cost estimates from Western Australia ([Australian Bureau of Resources and Energy Economics, 2012](#)), which provides a snapshot of costs in a particular year and from the U.S. ([U.S. Energy Information Administration, 2010, 2013, 2016, 2020](#)), which provides a time series of costs for each energy source. Appendix A.3 provides a description of these data sources and the assumptions made to obtain the full sequence of costs over time for Western Australia.

This reflects the fact that there are only two firms that are able to adjust in each period. Appendix C.4 provides details about the choice of Γ , the possible generator combinations for each firm.²⁸

5 Results

5.1 Wholesale Market Results

Table 2 provides estimates for the wholesale market costs, demand shocks, and capacity factors, as described in section 4.1. For the sake of computational feasibility, I use 2500 randomly selected half-hour intervals in the year 2015. Column 1 includes estimates of a model in which there is no correlation in the cost shocks and there is no correlation among wind capacity factors or demand shocks. Column 2 relaxes those constraints: it presents estimates of a model that allows for correlation in all of the shocks. Allowing for correlation appears to matter. Correlation both within and across sources is quite high, and the inclusion of correlation results in substantially lower variance in the cost shocks as well as more sensible estimates of average costs.

Estimates of average costs per MWh are approximately in line with industry estimates. Using estimates from the second column (with correlation in shocks), I estimate that the per-MWh cost of electricity produced by coal is 21.83 AUD / MWh and that for gas is 32.65 AUD / MWh. Even accounting for correlation in cost shocks, the variance of these costs is quite high across time. The standard deviation for each source respectively is 18.33 and 18.65.

I estimate that it is costly to use a high fraction of capacity but that the costs are not very large. The estimate of this cost, given by ζ_2 in the model, is 893.45 AUD for coal and 206.97 AUD for gas. Note that this is not a per-unit cost but rather the *total* cost paid for using all of a generator's capacity. The marginal cost is twice that cost divided by the generator's capacity. While capacities vary across generators, they are usually between 50 and 150 MW, so the marginal cost of using capacity is on the scale of a few dollars.²⁹

Wind capacity factors are estimated to be positively but weakly correlated with each other, with a correlation coefficient of 0.28. Wind capacity factors are virtually uncorrelated with demand.

²⁸Note that $\Pi_t(\mathcal{G})$ depends only on parameters estimated in the previous stage. I can therefore pre-compute this function for each $\mathcal{G} \in \Gamma$ (which is computationally difficult, see appendix C.1.2), which then remain the same for each candidate θ .

²⁹The range of capacities given is the capacity at the *half-hourly level* rather than hourly (since wholesale intervals take place in half-hourly intervals).

Table 2: Wholesale Market Estimates

	(1)	(2)
$\hat{\sigma}_{\text{coal}}$	71.767 (8.995)	18.334 (0.460)
$\hat{\sigma}_{\text{gas}}$	44.966 (1.428)	18.652 (0.491)
$\hat{\zeta}_{2,\text{coal}}$	6 354.212 (899.311)	893.452 (73.900)
$\hat{\zeta}_{2,\text{gas}}$	775.830 (63.720)	206.966 (30.963)
$\hat{\rho}_{\text{coal,coal}}$		0.764 (0.032)
$\hat{\rho}_{\text{gas,gas}}$		0.806 (0.041)
$\hat{\rho}_{\text{coal,gas}}$		0.774 (0.034)
X_{ϵ}		
$\hat{\mathbf{1}}_{\text{coal}}$	-69.746 (11.945)	21.831 (1.523)
$\hat{\mathbf{1}}_{\text{gas}}$	17.339 (2.367)	32.648 (1.025)
$\hat{\sigma}_{\log(\bar{Q})}$	0.172 (0.002)	0.172 (0.002)
$X_{\log(\bar{Q})}$		
$\hat{\mathbf{1}}_{\log(\bar{Q})}$	6.941 (0.003)	6.941 (0.003)
$\hat{\sigma}_{f^{-1}(\delta_{\text{wind}})}$	1.772 (0.012)	1.779 (0.013)
$X_{f^{-1}(\delta_{\text{wind}})}$		
$\hat{\mathbf{1}}_{f^{-1}(\delta_{\text{wind}})}$	-1.215 (0.021)	-1.274 (0.021)
$\hat{\rho}_{f^{-1}(\delta_{\text{wind}}),f^{-1}(\delta_{\text{wind}})}$		0.278 (0.008)
$\hat{\rho}_{f^{-1}(\delta_{\text{wind}}),\log(\bar{Q})}$		-0.020 (0.011)
$\hat{p}_{\delta_{\text{coal}}}$	0.987 (0.001)	0.987 (0.001)
$\hat{p}_{\delta_{\text{gas}}}$	0.987 (0.001)	0.987 (0.001)
year	2015	2015
num. obs.	2500	2500

5.2 Investment Decision Results

The wholesale market results provided in table 2 are used in the second stage dynamic parameter estimates to construct an estimate of yearly expected profits, $\hat{\Pi}(\mathcal{G})$. I use the estimates in the second column that allow for a rich correlation structure to construct these estimated profit functions. The investment decision parameter estimates are provided in table 3. The first column corresponds to the model specification in which firms can no longer adjust their generator sets 5 years after the last year in the data, and the second column corresponds to the specification in which this takes place 10 years after the last year in the data.

Table 3: Dynamic Estimates

	(1)	(2)	(3)
	$T_{add} = 5$	$T_{add} = 10$	$T_{add} = 15$
\hat{M}_{coal}	0.055 (0.008)	0.057 (0.007)	0.058 (0.007)
\hat{M}_{gas}	0.021 (0.029)	0.017 (0.030)	0.016 (0.030)
\hat{M}_{wind}	0.071 (0.025)	0.081 (0.048)	0.086 (0.055)
$\hat{\sigma}$	185.700 (54.845)	184.085 (44.229)	183.181 (41.091)

Note: Estimates are in 1 000 000 AUD.

T_{add} represents the number of additional periods after the final period in the data before firms can no longer add or retire new generators.

[NOTE: WORKING ON NEW ESTIMATES]

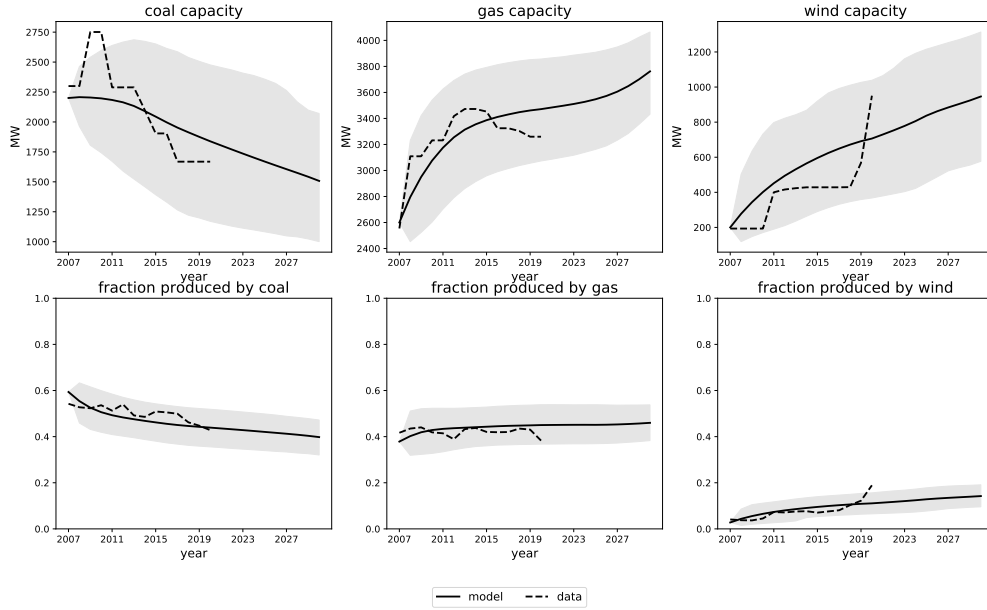
Figure 5 depicts the aggregate source-level capacities and fractions of total electricity production observed in the data and compares them to those predicted by the model. [NOTE: NEED TO PLOT MODEL DISTRIBUTION RATHER THAN JUST EXPECTATION - PROBABLY LOOKS BETTER THAN JUST THE EXPECTATION] I match the general patterns in the data reasonably well.

6 Counterfactuals

[THIS SECTION IS VERY MUCH STILL WORK IN PROGRESS]

The wholesale and dynamic results provided in tables 2 and 3 allow me to simulate the path of investment and production that firms undertake under counterfactual policies. In this section, I adopt the same modeling framework as in the dynamic estimation, in which strategic firms

Figure 5: Model Prediction vs. Data



Note: The model path in each plot is the expectation over realizations of the idiosyncratic shocks given the initial state.

receive shocks allowing them to adjust their generators. As in the model used in estimation, all generators of a given source are ex-ante identical (i.e., they have the same capacity and the same distribution of production costs). I simulate firms' investment decisions from an initial state (the first year in the data, 2007), and characterize the distribution of investment and production decisions.

In order to evaluate optimal policy, we need to construct a welfare function that takes as inputs these investment and production decisions. There are four components to the total welfare function. The first two are standard components of welfare: consumer surplus and firms' profits (which include the costs of new generators). The third component is the carbon externality, which is the sum of carbon emitted to produce electricity times the social cost of carbon. The final component is the blackout cost, which is the expected Megawatt-hours of electricity experiencing a blackout due to demand exceeding available supply times consumers' willingness to pay to avoid a Megawatt-hour of blackouts, which is referred to in the electricity literature as the *value of lost load*.^{30,31}

³⁰I assume that blackouts are rolling. If consumers demand 1 000 MWh in a given interval, but the available supply $\sum_g \bar{K}_{g,h}$ is only 900 MWh, then 100 MWh are randomly rationed. The consumers who are rationed receive *zero* electricity. These 100 MWh are multiplied by the value of lost load in order to determine the cost of the blackout in that interval. [SHOULD I ALSO CONSIDER THAT THERE IS A SYSTEM FAILURE WITH SOME PROBABILITY? THIS DOES HAPPEN IN PRACTICE.]

³¹In theory, the blackout cost is a part of consumer surplus, but the utility specification I use is meant

I consider changes in this welfare function, as I change policies. A policy is a tax or subsidy regime, such as a carbon tax or capacity payments. Subsidies are paid via a lump-sum transfer from consumers, and taxes are similarly rebated to consumers through a lump-sum transfer. Formally, the change in total surplus going from policy P to policy P' is given by

$$\begin{aligned}\Delta^{P \rightarrow P'} W_t = & \Delta^{P \rightarrow P'} C S_t \\ & + \Delta^{P \rightarrow P'} \sum_f \Pi_{f,t} \\ & - SCC \times \Delta^{P \rightarrow P'} \text{ carbon emissions} \\ & - VOLL \times \Delta^{P \rightarrow P'} \text{ MWh experiencing blackout,}\end{aligned}$$

and the change in total surplus over the entire time horizon is given by

$$\Delta^{P \rightarrow P'} \mathcal{W} = \mathbb{E} \left[\sum_{t=0}^{\infty} \beta^t \Delta^{P \rightarrow P'} W_t \right]. \quad (21)$$

The welfare function uses two values to convert everything into monetary terms that do not come from the model, namely the social cost of carbon (SCC) and the value of lost load ($VOLL$). In the following counterfactuals I use a range of plausible values for both costs as well as a baseline value for both costs for the results presented in the main text of the paper, given in table 4. Results for alternative values of the social cost of carbon and the value of lost load are given in Appendix D. Emissions rates used to calculate the yearly level of emissions are given in Appendix A.4.

Table 4: Baseline Cost

Variable	Value	Source
SCC	70 AUD / tonne CO ₂ -eq	National Academies of Sciences, Engineering, and Medicine (2017)
$VOLL$	50 000 AUD / MWh	Australian Energy Regulator (2019)

Note: Values are converted to 2015 AUD.

6.1 Electricity Market Policies

In this section I consider policies that directly address a market failure, both in isolation and as a policy bundle. In particular, I consider two policy tools, carbon taxes and capacity payments. Each of these policies will be static, in the sense that they do not vary over time, and this is known by the firms at all points in time. In Section 6.3 I relax this restriction.

to capture changes in prices and is not well-suited for considering the cost to consumers of zero electricity provided. In fact, using the specification outlined in Appendix B.3, the marginal utility at zero electricity for a consumer is infinite. Instead, I opt to use an outside value for the cost of a blackout, using a range of plausible values based on surveys conducted by the Western Australian grid operator. $\Delta^{P \rightarrow P'} C S_t$ is therefore measured as if consumers never experienced a blackout, and is therefore only a function of the quantity-weighted average price \bar{P}_t .

6.1.1 Policies in Isolation

First, I consider each of the policy tools in isolation. For each policy tool that I consider, I will set the other tool to a value of 0, then simulate forward from the state in year 2007 in the data to obtain the distribution of firms' investment decisions, using the model presented in section 3 and column 1 of the parameters in table 3. The goal of this exercise is to isolate the impact of each tool separately. In section 6.1.2 I consider complementarities between the policies.

Carbon Tax I consider a carbon tax levied on firms based on the emissions rate of each generator. Figure 6 presents the evolution over time of the expectation of aggregate capacities and production by energy source for no carbon tax, a small one, one at the baseline *SCC*, and one at twice the baseline *SCC*. Unsurprisingly, a carbon tax results in a decline in the use of coal, which is the most carbon-intensive technology. Even a small carbon tax results in a substantially faster decline in coal capacity, and as the tax increases, an increasingly small fraction of capacity is actually used to produce electricity. Interestingly, the impact on gas capacity is not monotonic in the size of the carbon tax. As the tax increases from 0 AUD / tonne, gas capacity increases in expectation for all years, but eventually the tax becomes high enough that firms begin to retire gas generators, especially in the latter part of the sample. A small tax has little impact on the amount of wind capacity, but as it increases, the tax increases both the level in the long-run as well as the level in the short-run. A large carbon tax is required in order to induce firms to make large investments in wind early on in the sample while the cost of wind generators is still very high.

Figure 7 plots the expected present discount welfare across a range of carbon taxes. It breaks welfare into the four cost components: producer surplus, consumer surplus, emissions cost, and blackout cost. The final panel shows total welfare, which is the sum of these four [NOTE: REMOVE 'PROVISION COST' PANEL, NOT RELEVANT.] Carbon taxes are paid by generators and transferred to consumers in a lump sum payment. Emissions taxes unsurprisingly disincentive producing using carbon-intensive technologies, leading to a decline in the emissions cost as the tax increases. Blackout costs, however, are monotonically increasing in the carbon tax: as the tax increases, reliable thermal generators retire, replaced by wind generators, which are less reliable. Less intuitively, consumer surplus is decreasing in the carbon tax, and the producer surplus is increasing. Given that carbon taxes are paid by generators and rebated back to consumers, this may be a surprising result. This result is driven by a pass-through rate of the tax of over 100%. While pass-through rates are usually less than 100%, an empirical literature has found carbon tax pass-through rates of greater than 100% in electricity markets, including in Australia during a brief period in time in which

Figure 6: Impact of Carbon Tax on Investment and Production

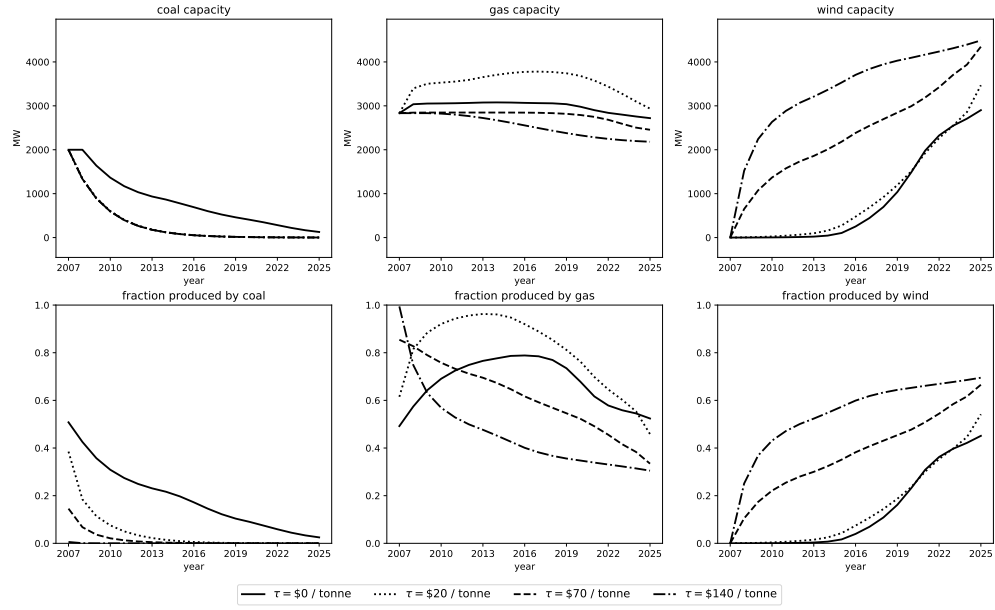
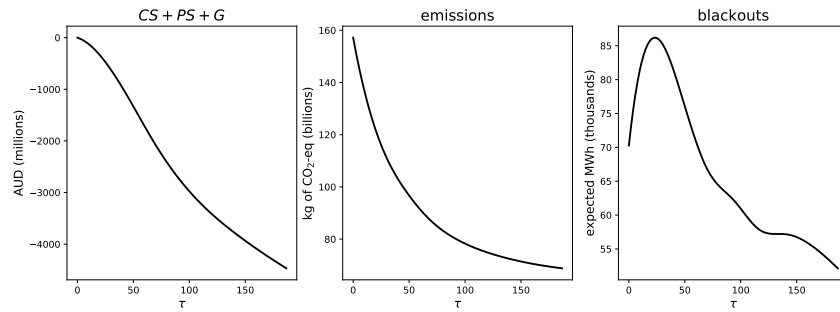


Figure 7: Welfare under Carbon Tax



Note: Welfare measures are the present discounted expected value, using the firms' discount factor recovered in the dynamic estimation stage.

a carbon tax was adopted (Nazifi *et al.* , 2021).³² [NOTE: ADD A PLOT OF OPTIMAL POLICIES AS A 2D FUNCTION OF *VOLL* AND *SCC*.]

Capacity Payments I next consider the impact of capacity payments. I consider a range of payment sizes, including no payments. Payments are financed via a lump sum transfer from consumers. This corresponds to what is known as the *energy only* model in restructured electricity markets (seen, for example, in Texas and in the National Electricity Market in Australia covering the eastern side of the country). A major policy question is not only the size of payments but whether to include payments at all. This counterfactual speaks to the impact of this policy tool on the frequency of blackouts (the main reason this tool is adopted) as well as secondary effects, such as how investment in different energy sources responds. For each capacity payment policy, I impose that capacity credit prices remain the same across time (as opposed to in the data in which the capacity credit price varies from year-to-year). The rules regarding penalties firms pay if committed capacity is unavailable remain the same as that presented earlier in the model. [I COULD LOOK AT A MARKET DESIGN QUESTION OF HOW RENEWABLES QUALIFY FOR THESE PAYMENTS, BUT I'M CURRENTLY NOT CONSIDERING THIS.]

Figure 8 is analogous to figure 6; it presents the expectation of aggregate capacity and production for three different levels of the capacity payments: no, small, and large capacity payments. The small and large payment levels correspond to the minimum and maximum capacity credit prices that I observe in my sample (\$98 000 and \$186 000 per MW, respectively). Capacity payments appear to have a large impact on the level of coal in the market. Without these payments, coal capacity declines toward zero over the sample period because the cost of maintenance outweighs the profits received (note that there is no carbon tax here). However, with the maximum payment value observed in the data, the probability of retirement of coal plants declines considerably. This results in less investment in gas, and in fact at the high payment value, since coal is on average cheaper than gas, gas capacity declines. There does not appear to be a substantial impact on wind.

I plot welfare in figure 9. Producers, unsurprisingly, benefit from the capacity payments, and consumer surplus declines. The likelihood of blackouts declines, but the emissions cost increases, primarily due to the payments increasing the fraction electricity produced by more carbon-intensive coal as opposed to gas, rather than significant changes in wind versus the fossil fuel generators. Using the baseline *VOLL* and *SCC*, total welfare is maximized at an

³²The carbon tax in Australia was in effect between July 2012 and July 2014, when it was repealed after a change in government. Importantly for this study, due to the political opposition to this tax, it was widely expected to be temporary. In my estimation, I therefore assume that firms predict the end of the temporary nature of the tax.

Figure 8: Impact of Capacity Payments on Investment and Production

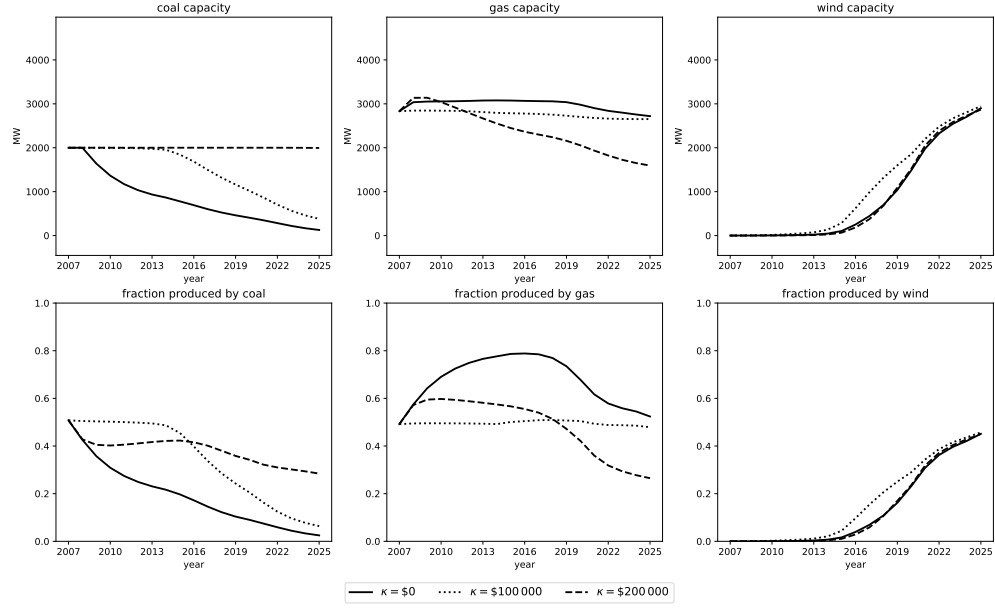
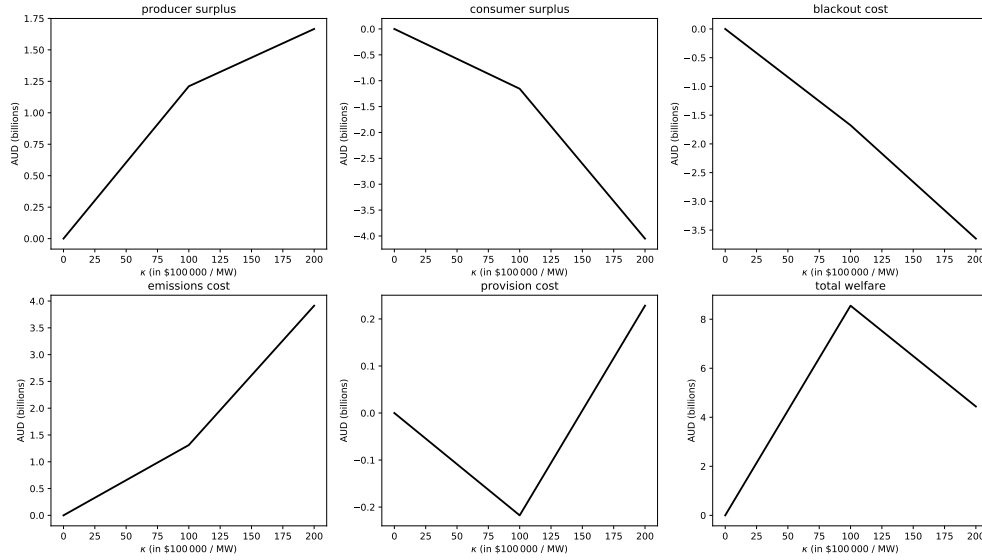


Figure 9: Welfare under Capacity Payments



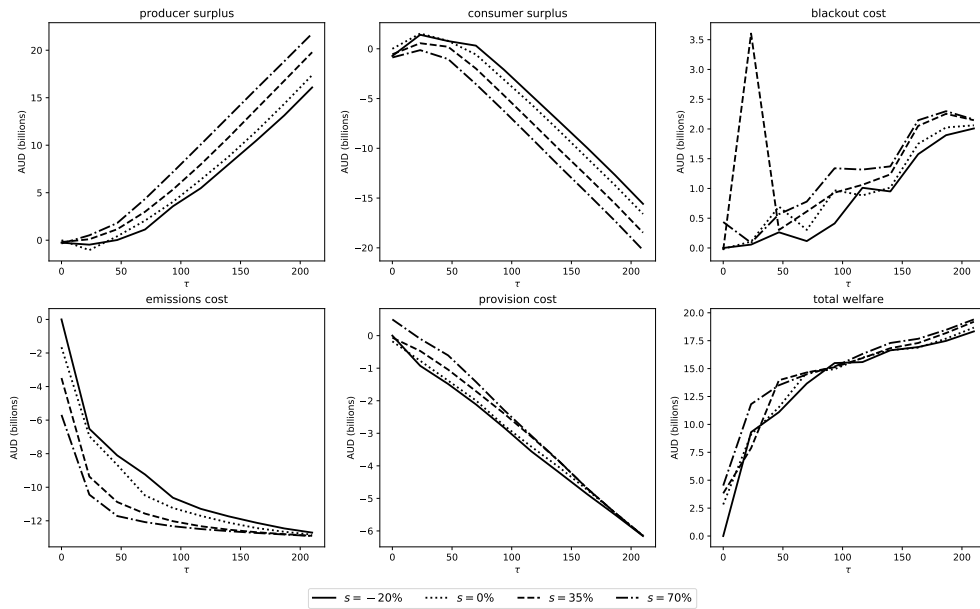
Note: Welfare measures are the present discounted expected value, using the firms' discount factor recovered in the dynamic estimation stage.

intermediate value of capacity payments. [NOTE: ADD A PLOT OF OPTIMAL POLICIES AS A 2D FUNCTION OF $VOLL$ AND SCC .]

6.1.2 Policy Bundle

I next consider the policies jointly. Figure 10 plots welfare (and its components introduced earlier) as a function of the carbon tax under the high value capacity payment from the previous section. [NOTE: REDO THIS GRAPH WITH EACH LINE AS A CAPACITY

Figure 10: Welfare under with Capacity Payments



Note: Welfare measures are the present discounted expected value, using the firms' discount factor recovered in the dynamic estimation stage. I use the large capacity payment in these counterfactual simulations.

PAYMENT LEVEL RATHER THAN A SUBSIDY. EXPLORE SUBSIDIES IN THE NEXT SECTION.] Blackout costs are more than an order of magnitude smaller under even high carbon taxes with capacity payments.

6.2 Carbon Taxes vs. Renewable Investment Subsidies

Table 5: Comparing Environmental Policies

Δ emissions (billions CO ₂ -eq)	policy	policy value	Δ blackouts (thousands MWh)	Δ CS (billions AUD)	Δ PS (billions AUD)	Δ G (billions AUD)	Δ (CS + PS + G) (billions AUD)
0	carbon tax	0.0	0.0	0.0	0.0	0.0	0.0
	renew. prod. subs.	0.0	0.0	0.0	0.0	0.0	0.0
	renew. inv. subs.	0.0	0.0	0.0	0.0	0.0	0.0
10	carbon tax	4.5	6.1	-0.8	0.1	0.6	-0.0
	renew. prod. subs.	5.7	10.7	0.2	0.2	-0.2	0.1
	renew. inv. subs.	49.2	3.5	0.2	0.7	-2.4	-1.5
20	carbon tax	9.6	11.0	-1.7	0.3	1.3	-0.1
	renew. prod. subs.	14.1	25.5	0.4	0.7	-0.8	0.3
	renew. inv. subs.	82.4	6.2	0.4	1.4	-6.0	-4.2
30	carbon tax	15.8	14.6	-2.8	0.5	2.0	-0.2
	renew. prod. subs.	23.8	38.0	0.7	1.5	-1.7	0.5
	renew. inv. subs.	-	-	-	-	-	-
40	carbon tax	24.0	15.9	-4.2	0.9	2.8	-0.4
	renew. prod. subs.	35.0	47.4	1.1	2.5	-3.0	0.5
	renew. inv. subs.	-	-	-	-	-	-
50	carbon tax	34.9	13.4	-6.0	1.4	3.7	-0.8
	renew. prod. subs.	55.9	57.2	1.7	5.1	-5.8	1.0
	renew. inv. subs.	-	-	-	-	-	-

Note: Changes in emissions, blackouts, and welfare variables are all in presented expected discounted values, which are the relevant values for evaluating the welfare function given in equation 21. Since simulated values are along a discrete grid, to back out the policy value that yields a given change in emissions, I interpolate values using cubic splines. I then use the interpolation to determine the policy value yielding the given change in emissions. For blackouts and welfare variables, I also use cubic spline interpolation, taking the implied policy value and determining the corresponding interpolated blackout or welfare variable value. For some of the higher levels of emissions reductions, there does not exist a renewable investment subsidy that would yield that level of an emissions reduction. In this case, the values in the corresponding columns are replaced with “-”.

Table 6: Comparing Environmental Policies with Capacity Payment

Δ emissions (billions CO ₂ -eq)	policy	policy value	Δ blackouts (thousands MWh)	Δ CS (billions AUD)	Δ PS (billions AUD)	Δ G (billions AUD)	Δ (CS + PS + G) (billions AUD)
0	carbon tax	2.0	-65.1	0.0	0.7	-0.9	-0.2
	renew. prod. subs.	1.9	-65.2	0.5	0.7	-1.3	-0.2
	renew. inv. subs.	24.3	-65.2	0.5	0.9	-2.1	-0.7
10	carbon tax	6.5	-64.1	-0.8	0.8	-0.3	-0.3
	renew. prod. subs.	8.5	-62.8	0.7	0.9	-1.6	0.1
	renew. inv. subs.	63.8	-64.4	0.7	1.6	-4.8	-2.5
20	carbon tax	11.4	-63.2	-1.6	1.0	0.3	-0.3
	renew. prod. subs.	17.0	-58.3	1.0	1.5	-2.1	0.4
	renew. inv. subs.	96.5	-63.6	1.0	2.4	-9.4	-6.0
30	carbon tax	17.4	-62.4	-2.6	1.2	1.0	-0.4
	renew. prod. subs.	26.4	-53.0	1.4	2.2	-3.0	0.6
	renew. inv. subs.	-	-	-	-	-	-
40	carbon tax	25.3	-61.6	-3.9	1.5	1.8	-0.6
	renew. prod. subs.	37.9	-47.7	1.8	3.4	-4.5	0.7
	renew. inv. subs.	-	-	-	-	-	-
50	carbon tax	35.8	-61.0	-5.6	2.0	2.7	-0.9
	renew. prod. subs.	60.8	-41.9	2.6	6.2	-7.4	1.4
	renew. inv. subs.	-	-	-	-	-	-

Note: All of the notes in table 5 apply. Policies in this table are additionally simulated with a capacity payment equal to 50 000 AUD / MW / year. Changes are with respect to the *laissez-faire* market without capacity payments *or* environmental policies. Note that the addition of a capacity payment impacts emissions even without any environmental policy; therefore, the policy values at Δ emissions = 0 are not zero.

An alternative environmental policy tool that is often employed instead of (or sometimes in addition to) carbon taxes is a renewable investment subsidy. In this section I consider how using renewable investment subsidies compares to a carbon tax. These subsidies impact the extensive margin of adjustment, capacity, rather than the intensive margin, production, that carbon taxes impact. The subsidies fail to directly impact the production decisions between coal and gas, but they can increase the level of wind investment. Moreover, wind production tightly follows wind investment since it has a marginal cost of virtually zero. I consider subsidies s as a fraction of total cost (i.e., the net cost per MW of a wind generator in year t is $(1 - s)C_{\text{wind},t}$), paid for in a lump sum transfer from consumers. Figure 11 presents the expectation of aggregate capacity and production for several different levels of the policy tools. Specifically, figure 11 plots an investment tax, no subsidy, a moderately-sized subsidy, and a very large subsidy. The larger the wind investment subsidy, the higher the expected investment level, and the sooner the market reaches an expected level. The level of fossil fuels responds to the level of wind in the market, and coal and gas display an interesting substitutability. With a negative subsidy, gas capacity is (relatively) high, and coal capacity is low. With an increase in the subsidy, gas capacity declines, and coal actually increases, but for a sufficiently high subsidy, both coal and gas capacity declines.

Figure 12 plots welfare for a range of investment subsidies. [WHY THE DIP IN PS? NOT SURE.] Unlike with a carbon tax, as the subsidy increases, the probability of blackouts declines. Reliable coal and gas generators do not decline nearly as much from a renewable investment subsidy as they do for carbon taxes. With only smaller decline in coal and gas capacity, and some increase in capacity due to wind (even if less reliable), the frequency of blackouts declines in the subsidy. Predictably, emissions also decline; however, the decline in emissions is less than that obtained from a high carbon tax.

6.3 Policy Timing

[HAVE NOT DONE THIS YET, BUT IDEA IS TO LOOK AT WELFARE AS I DELAY THE IMPLEMENTATION OF THE NEW POLICY. DOES GIVING TIME FOR FIRMS TO ADJUST *PRIOR* TO POLICY TAKING EFFECT YIELD WELFARE GAINS?]

7 Conclusion

[NEED TO ADD]

Figure 11: Impact of Renewable Investment Subsidy on Investment and Production

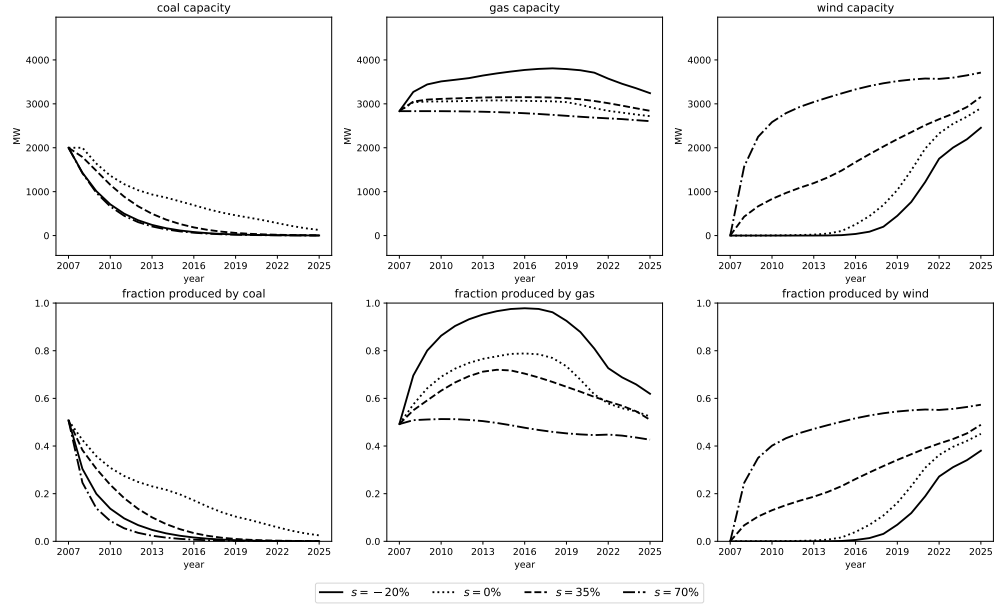
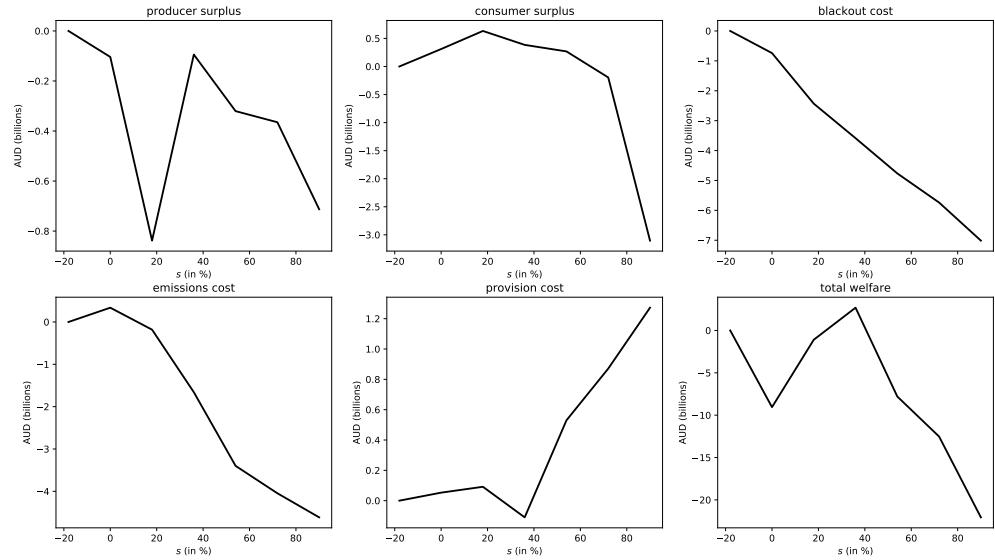


Figure 12: Welfare under Renewable Investment Subsidy



Note: Welfare measures are the present discounted expected value, using the firms' discount factor recovered in the dynamic estimation stage.

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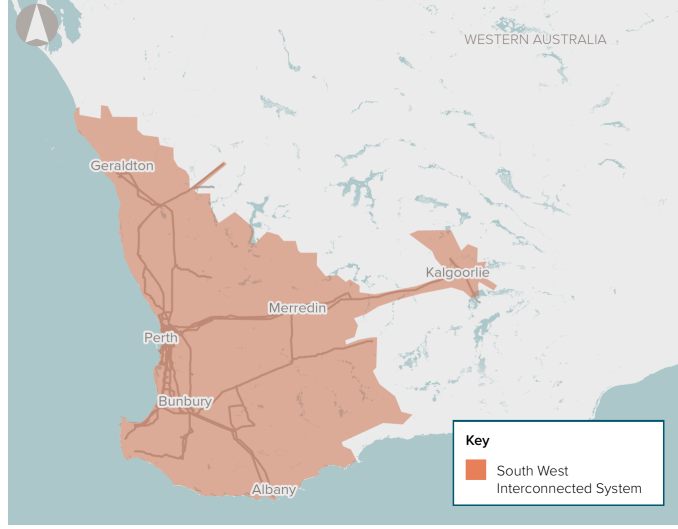
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A Additional Industry Details

A.1 South West Interconnected System

Figure 13: Map of South West Interconnected System



Source:

<https://www.infrastructureaustralia.gov.au/map/south-west-interconnected-system-transformation>

A.2 Capacity Obligation Penalty Rules

Approximated formula for the paper [NOTE TO SELF: NEED TO EXPAND, EXPLAIN HOW SIMPLIFYING FROM THE FORMULA IN WEM RULES]:

The energy source-specific component of the refund factor is

$$\lambda_s = \begin{cases} \frac{1}{17280} & \text{if } s \in \{\text{coal, gas}\} \\ \frac{1}{1440} & \text{if } s \in \{\text{wind}\} . \end{cases} \quad (22)$$

A.3 Capacity Costs

Generator cost data comes from two different sources. The first source is a series of reports produced by the U.S. Energy Information Administration (EIA) on capital costs of electricity generators (U.S. Energy Information Administration, 2010, 2013, 2016, 2020). Each report provides capital costs in USD / kW for different generator technologies. The reports are more detailed than the general categories I use in this paper (coal, gas, and wind). In general, I try to select capital costs from specific categories that represent the types of new generators

commonly built today. For coal, I use the capital costs for ultra-supercritical coal plants.³³ For gas, I use the capital costs for a combined cycle gas turbine plant.³⁴ Finally, for wind, I use the capital costs of on-shore wind generators. All of these costs are summarized in table 7.

Table 7: EIA Generator Cost Estimates

Year	Coal (in USD / MW)	Gas (in USD / MW)	Wind (in USD / MW)
2010	3 167 000	978 000	2 438 000
2013	3 246 000	917 000	2 213 000
2016	3 636 000	978 000	1 877 000
2019	3 676 000	1 084 000	1 677 000

Note: U.S. Energy Information Administration (2010, 2013, 2016, 2020) report these values in USD / kW, but I convert the values here to USD / MW because the units used in this paper are MW and MWh.

The second source is the 2012 Australian Energy Technology Assessment ([Australian Bureau of Resources and Energy Economics, 2012](#)), which I shall refer to as AETA. While this report only provides a snapshot in time, unlike the series of EIA reports that construct a panel, AETA does helpfully provide cost estimates specific to the South West Interconnected System in Western Australia that I study in this paper. I therefore use the EIA reports to construct a time series for each source and AETA to convert the time series based on U.S. estimates to those for the electricity market in Western Australia. As with the EIA reports, AETA provides much more detailed generator categories than I use in this paper. I use the same representative categories as those described above: ultra-supercritical plants for coal, combined cycle plants for gas, and on-shore for wind. Table 8 provides the cost estimates that I use.

Table 8: Australian Energy Technology Assessment Generator Cost Estimates

Year	Coal (in AUD / MW)	Gas (in AUD / MW)	Wind (in AUD / MW)
2012	3 124 000	1 111 000	2 530 000

In order to construct a complete time series of generator costs over time for Western Australia, I first interpolate the time series provided by the EIA report. For each energy source, I linearly interpolate values in years not covered by an EIA report,³⁵ providing me with $\hat{C}_{s,t}^{EIA}$ for each $t \in [2010, 2019]$. Next, I convert the interpolated EIA estimates to those for Western Australia. To do so, I assume that Western Australia costs are a source-specific proportion α_s of the

³³Ultra-supercritical power plants operate at high temperatures and pressures, requiring less coal per MWh of electricity. They are the current commonly-used technology for coal plants.

³⁴Combined cycle power plants use exhaust heat from gas turbines to power steam turbines in order to generate more electricity for a given amount of natural gas. They are the currently commonly-used technology for natural gas plants.

³⁵The sample covers a few years before 2010. For these years, I linearly extrapolate, but not for the years past 2019. For those past 2019, I use a separate method, explained later in this description.

EIA costs, common over time. Explicitly, I assume

$$C_{s,t}^{WA} = \alpha_s C_{s,t}^{EIA}.$$

Since I have cost estimates for Western Australia in 2012, I can recover $\{\alpha_s\}_s$:

$$\hat{\alpha}_s = \frac{C_{s,2012}^{WA}}{\hat{C}_{s,2012}^{EIA}}.$$

These estimates allow me to construct the Western Australian time series through 2019. The model includes years past 2019. For these years, I apply a line of best fit for each source based on $\{\hat{C}_{s,t}^{WA}\}_{t=2007}^{2019}$, and use this line to extend cost estimates through 2025. Some versions of the model use years past 2025. For these versions, I assume that $\hat{C}_{s,t}^{WA} = \hat{C}_{s,2025}^{WA}$ for all $t > 2025$.

A.4 Emissions Rates

The Australian Energy Technology Assessment ([Australian Bureau of Resources and Energy Economics, 2012](#)) described in the previous section (section A.3) reports emissions rates for different generator technologies. This emissions rate corresponds to the value r_s in the model presented in section 3). As with capacity costs described above, this report provides more detailed generator technologies than the broad categories used in the model. I use the same representative technologies for emissions rates as in section A.3 for capacity costs. Table 9 provides a list of emissions rates.

Table 9: Australian Energy Technology Assessment Emissions Rates

Coal	Gas	Wind
(in kgCO ₂ -eq / MWh)	(in kgCO ₂ -eq / MWh)	(in kgCO ₂ -eq / MWh)
783	358	0

Note: kgCO₂-eq means kg of CO₂-equivalent greenhouse gases. Greenhouse gases other than CO₂ are converted to CO₂-equivalent terms on the basis of global-warming potential. For example, 1 kg of methane is equal to 25 kgCO₂-eq.

B Model Details

B.1 Discussion of Wholesale Market Modeling Choices

Two modeling choices differentiate this model of the wholesale market from some of the recent work estimating costs in wholesale markets (e.g., [Reguant \(2014\)](#)). These modeling decisions

make computation of the oligopolistic wholesale market across an extremely large number of possible sets of generators feasible, which is necessary for nesting a model of wholesale profits in a long-run model of generator investment. Moreover, I argue here that the more restrictive assumptions that I make for tractability do not significantly affect the results.

First, I model firms as competing in quantities (as in [Bushnell *et al.* \(2008\)](#)) rather than bidding in an auction (as in [Wolak \(2007\)](#) and [Reguant \(2014\)](#)). A supply function equilibrium is generally nonunique and computationally difficult. As noted by [Klemperer & Meyer \(1989\)](#), a supply function equilibrium is bounded between the competitive and Cournot equilibria, and the steeper the supply functions, the closer the equilibrium is to Cournot. Using bidding data from the wholesale electricity market, I find that supply functions are [GET THE NUMBER FOR THIS] times steeper for the largest firms, which are the firms that I assume compete à la Cournot, than for the smallest firms, which are those that I assume are in the competitive fringe.³⁶

Second, I model the wholesale market as a static decision, in which the production decision in a given period does not affect costs in a future period. The alternative approach used in the wholesale market estimation literature adds start-up costs and sometimes ramp-up costs, which mean it is cheaper for a firm to produce in given period if it produced in the previous period.³⁷ Adding these dynamic costs would make the wholesale market a dynamic game since firms have market power. Given the heavy computational burden of computing such a game (along with the issue of choosing among potentially many equilibria), adding these costs would be infeasible. While [Mansur \(2008\)](#) notes that ignoring these costs can bias estimates and welfare, I believe that this bias is likely to be small in my setup. [Reguant \(2014\)](#) finds that these costs are relatively small for natural gas plants and much larger for coal plants. In a preview of the results, I find that policies that incentivize wind tend to reduce investment in coal capacity. Large start-up costs would likely make coal even more costly under such policies (due to the intermittent nature of wind), so not including start-up costs may bias coal investment levels upward. Since these levels are already very low in most of the counterfactuals I study, I do not believe that the lack of start-up costs impacts the results in a significant way.

³⁶One computationally tractable alternative that computes a supply function equilibrium is that introduced by [Karaduman \(2020a\)](#), which estimates best response functions and then uses those to determine equilibrium changes from the introduction of batteries. Unlike in [Karaduman \(2020a\)](#), generators make investment decisions, so these best response functions are equilibrium objects that are likely to change with large changes in the sets of generators in the market induced by the policies I study. This supply function equilibrium approach is therefore not applicable to the setting I study.

³⁷See, for example, [Reguant \(2014\)](#) and [Butters *et al.* \(2021\)](#).

B.2 Wholesale Market Equilibrium

[UPDATE THIS SECTION W/ NEW VERSION IN WHICH ALSO CONSTRAINT FROM BELOW]

In the interval h , there is a demand shock \bar{Q}_h , and firms draw $\zeta_{1,h}$, δ_h .

The competitive firm takes prices as given, yielding the competitive supply curve

$$Q_h^c(P_h) = \alpha_h + \beta_h P_h, \quad (23)$$

where

$$\begin{aligned} \alpha_{t,h} &= -\frac{\sum_s \zeta_{1,c,s,t,h} \prod_{s' \neq s} 2\zeta_{2,s'} K_{c,s',t,h}^{-2}}{\prod_s 2\zeta_{2,s} K_{c,s,t,h}^{-2}} \\ \beta_{t,h} &= \frac{\sum_s \prod_{s' \neq s} 2\zeta_{2,s'} K_{c,s',t,h}^{-2}}{\prod_s 2\zeta_{2,s} K_{c,s,t,h}^{-2}}. \end{aligned}$$

Then the strategic firms face the following inverse residual demand curve

$$\begin{aligned} P_h(\mathbf{q}_h) &= \frac{\bar{Q}_h - \sum_{g \in \mathcal{G}} q_{g,h} - \alpha_h}{\beta_h} \\ &= a_h - b_h \sum_{g \in \mathcal{G}} q_{g,h}. \end{aligned} \quad (24)$$

The set of generators that could potentially hit the capacity constraint is $\wp(\mathcal{G})$, where $\wp(A)$ denotes the power set of A .

Consider $\Omega \in \wp(\mathcal{G})$, where Ω are the generators that are constrained. Then, for $g \notin \Omega$, the first order condition is

$$\alpha_h - b_h \sum_{g' \notin \mathcal{G}_{-n(g)}} q_{g',h} - 2b_h \sum_{g' \in \mathcal{G}_{n(g)}} q_{g',h} = \zeta_{1,g,h} + \zeta_{2,g,h} q_{g,h},$$

where $n(s)$ denotes the identity of the firm to which generator g belongs, \mathcal{G}_n denotes the set of generators belonging to the firm n , and $\mathcal{G}_{-n} = \mathcal{G} \setminus \mathcal{G}_n$. This expression yields

$$\begin{aligned} q_{g,h}^* &= \frac{\alpha_h - b_h \sum_{g' \in \mathcal{G}_{-n(g)}} q_{g',h} - 2b_h \sum_{g' \in \mathcal{G}_{n(g)} \setminus \{g\}} q_{g',h} - \zeta_{1,g,h}}{2b_h + \zeta_{2,g,h}} \\ &= \frac{\alpha_h - b_h \left(\sum_{\substack{g' \in \mathcal{G}_{-n(g)}: \\ g' \notin \Omega}} q_{g',h} + \sum_{\substack{g' \in \mathcal{G}_{-n(g)}: \\ g' \in \Omega}} \bar{K}_{g',h} + 2 \sum_{\substack{g' \in \mathcal{G}_{n(g)} \setminus \{g\}: \\ g' \notin \Omega}} q_{g',h} + 2 \sum_{\substack{g' \in \mathcal{G}_{n(g)} \setminus \{g\}: \\ g' \in \Omega}} \bar{K}_{g',h} \right) - \zeta_{1,g,h}}{2b_h + \zeta_{2,g,h}}. \end{aligned} \quad (25)$$

Let $\mathbf{q}_{-\Omega,h}^* = [q_{g,h} \forall g \notin \Omega]'$, and let $\mathbf{K}_{-\Omega,h}$, $\bar{\mathbf{K}}_{-\Omega,h}$, $\zeta_{1,-\Omega,h}$, and $\zeta_{2,-\Omega,h}$ be defined analogously.

Then I can rewrite equation 25 as

$$\mathbf{q}_{-\Omega,h}^* = \frac{1}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \odot \left(\alpha_h - b_h \left(\Xi_{-\Omega,\Omega} \bar{\mathbf{K}}_{\Omega,h} + \Xi_{-\Omega,-\Omega} \mathbf{q}_{-\Omega,h}^* \right) - \boldsymbol{\zeta}_{1,-\Omega,h} \right),$$

where \odot is the Hadamard product, division is element-wise, and

$$\Xi_{A,B} = \begin{bmatrix} \ddots & & \\ & \xi_{g \in A, g' \in B} & \\ & & \ddots \end{bmatrix}_{|A| \times |B|},$$

where

$$\xi_{g,g'} = \begin{cases} 0 & \text{if } g = g' \\ 1 & \text{if } n(g) \neq n(g') \\ 2 & \text{if } g \neq g' \text{ and } n(g) = n(g'). \end{cases}$$

I can then rewrite as

$$\mathbf{q}_{-\Omega,h}^* = \left(I_{|-\Omega|} + \frac{b_h}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \mathbf{1}'_{|-\Omega|} \odot \Xi_{-\Omega,-\Omega} \right)^{-1} \left[\frac{1}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \odot \left(a_h - b_h \Xi_{-\Omega,\Omega} \bar{\mathbf{K}}_{\Omega,h} - \boldsymbol{\zeta}_{1,-\Omega,h} \right) \right], \quad (26)$$

where I_n is the identity matrix of size n and $\mathbf{1}_n$ is a column vector of ones of size n .

I can now characterize the conditions which would yield Ω as the firm-sources that are constrained while the firm-sources in $\mathcal{G} \setminus \Omega$ are unconstrained:

$$\left(I_{|-\Omega|} + \frac{b_h}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \mathbf{1}'_{|-\Omega|} \odot \Xi_{-\Omega,-\Omega} \right)^{-1} \left[\frac{1}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \odot \left(a_h - b_h \Xi_{-\Omega,\Omega} \bar{\mathbf{K}}_{\Omega,h} - \boldsymbol{\zeta}_{1,-\Omega,h} \right) \right] \leq \bar{\mathbf{K}}_{-\Omega,h} \quad (27)$$

and

$$\frac{1}{2b_h + \boldsymbol{\zeta}_{2,-\Omega,h}} \odot \left(a_h - b_h \left(\Xi_{\Omega,-\Omega} \mathbf{q}_{-\Omega,h}^* + \Xi_{\Omega,\Omega} \bar{\mathbf{K}}_{\Omega,h} \right) - \boldsymbol{\zeta}_{1,\Omega,h} \right) \gg \bar{\mathbf{K}}_{\Omega,h}. \quad (28)$$

Note that $\wp(\mathcal{G})$ constitutes the entire set of possible configurations of firms' capacity constraints binding.

Proposition 1. *There exists a unique $\Omega \in \wp(\mathcal{G})$ such that all inequalities in Equations 27 and 28 hold.*

Proof. See Appendix F. □

Using Proposition 2, I can therefore compute the wholesale market equilibrium for a given set of market conditions $(Q_h, \mathbf{K}_h, \bar{\mathbf{K}}_h, \boldsymbol{\zeta}_{1,h}, \boldsymbol{\zeta}_{2,h})$ by computing $\mathbf{q}_h^*(\Omega)$ for each $\Omega \in \wp(\mathcal{G})$ and selecting the single Ω such that all inequalities in Equations 27 and 28 hold.

B.3 End-Consumer Demand

B.3.1 Consumer's Problem

A measure 1 of consumers has utility in a given interval h of

$$u_h(q, P) = \frac{\xi_h}{1 - 1/\epsilon} q^{1-1/\epsilon} - Pq, \quad (29)$$

where P is the *end-consumer price* (rather than the wholesale price that varies with the interval h). The utility function is scaled such that the marginal utility of money is 1. The consumers' first order conditions imply that the optimal electricity consumption is

$$q_h^*(P) = \left(\frac{\xi_h}{P} \right)^\epsilon.$$

I assume that $\log(\xi_h) \sim \mathcal{N}(\mu, \sigma^2)$. Therefore, since $\bar{Q}_h = \int_0^1 q_h^* di$,

$$\log(\bar{Q}_h) \sim \mathcal{N}(\epsilon\mu - \epsilon \log(P), \epsilon^2 \sigma^2).$$

Note that $E\bar{Q}(P) := \mathbb{E}[\bar{Q}_h | P] = \exp(\epsilon\mu - \epsilon \log(P) + \frac{\epsilon^2 \sigma^2}{2})$, and the price elasticity is therefore given by

$$\frac{d \log E\bar{Q}(P)}{d \log P} = -\epsilon. \quad (30)$$

Consumers thus have a constant price elasticity.

Using this utility function, I can determine expected consumer surplus as a function of the end-consumer price.

$$\begin{aligned} u_h(q^*(P), P) &= \frac{\xi_h}{1-1/\epsilon} \left(\frac{\xi_h}{P} \right)^{\epsilon-1} - P \left(\frac{\xi_h}{P} \right)^\epsilon \\ &= \frac{1}{\epsilon-1} P^{1-\epsilon} \xi_h^\epsilon. \end{aligned}$$

The expected change in consumer surplus going from P_1 to P_2 , $E\Delta CS(P_1, P_2)$ is therefore given by

$$\begin{aligned} E\Delta CS(P) &= \mathbb{E}[u_h(q^*(P_2), P_2) - u_h(q^*(P_1), P_1)] \\ &= \frac{1}{\epsilon-1} \exp\left(\epsilon\mu + \frac{\epsilon^2 \sigma^2}{2}\right) (P_2^{1-\epsilon} - P_1^{1-\epsilon}). \end{aligned} \quad (31)$$

B.3.2 End-Consumer Price

Note that the price in equation 29 is the end-consumer price, which is not necessarily the same as the wholesale price or even the average wholesale price. Consumers buy electricity

from intermediaries. I assume that intermediaries set prices equal to the marginal cost of providing electricity (over the long-run, averaging over the prices in the wholesale markets). I make this assumption because Western Australia regulates retail electricity prices. I assume that

$$P_t^{consumer}(\bar{P}_t) = c_{retail} + c_{network} + \bar{P}_t, \quad (32)$$

where \bar{P}_t is the quantity-weighted average wholesale price defined in equation 8 and the elasticity comes from [Deryugina et al. \(2020\)](#),³⁸ c_{retail} is the marginal retail cost of delivering electricity, and $c_{network}$ is the marginal cost of using the network to deliver electricity. Both of these marginal costs come from [AEMC \(2014\)](#) and are given in table 10.

Table 10: Marginal Costs of Retail Electricity

Price Component	Cost (in AUD / MWh)	Source
c_{retail}	29.50	AEMC (2014)
$c_{network}$	131.40	AEMC (2014)
\bar{P}_t	$\bar{P}_t(\mathcal{G})$ (equation 8)	model, Deryugina et al. (2020)

C Computational Details

C.1 Wholesale Market Equilibrium

C.1.1 Identifying Capacity Constrained Firms

[UPDATE THIS SECTION W/ NEW VERSION IN WHICH ALSO CONSTRAINT FROM BELOW]

While it would be possible in theory to compute the equilibrium for each $\Omega \in \wp(\mathcal{G})$ and determine which Ω satisfies all of the constraints, this becomes computationally infeasible with a large number of generators, as the problem scales exponentially with G . In this section I present an equivalent algorithm capable of solving for the set of constrained firm-energy sources that scales linearly, rather than exponentially, with G . I denote this set of constrained firm Ω as

$$\Omega_h^* := \{\Omega \in \wp(\mathcal{G}) : \text{inequalities (27) and (28) hold}\}.$$

Note that II can rewrite the first set of inequalities given by equation 27 in terms of the

³⁸I use the two-year elasticity estimate rather than their estimates of the elasticity in the shorter-run (such as six months). The choice of the two-year elasticity is to capture long run dynamics in demand when consumers can react to changing prices (by, e.g., buying more energy efficient appliances, installing solar panels, etc.).

demand intercept a_h . Since the demand intercept is common to all firm-sources, I can use the inequalities written in terms of the demand intercept to order the sequence in which firm-sources would bind as I raise a_h from $-\infty$. The inequality given by equation 27 becomes

$$a_h \Psi^{-1} \gamma \leq \bar{\mathbf{K}}_{-\Omega, h} + \Psi^{-1} \left(\gamma \odot \left(b_h \Xi_{-\Omega, \Omega} \bar{\mathbf{K}}_{\Omega, h} + \boldsymbol{\zeta}_{1, -\Omega, h} \right) \right), \quad (33)$$

where, for notational compactness, I have defined $\Psi = I_{|-\Omega|} + \frac{b_h}{2b_h + \boldsymbol{\zeta}_{2, -\Omega, h}} \mathbf{1}'_{|-\Omega|} \odot \Xi_{-\Omega, -\Omega}$ and $\gamma = \frac{1}{2b_h + \boldsymbol{\zeta}_{2, -\Omega, h}}$.

Note that $\Psi^{-1} \gamma$ can be positive or negative. If we Hadamard multiply this quantity by both sides of Equation 33, the inequality will flip whenever this quantity is negative. We can rewrite Equation 33 as

$$a_h \begin{cases} \leq \\ \geq \end{cases}_{\text{sgn}(\Psi^{-1} \gamma)} \underbrace{\Psi^{-1} \gamma \odot \bar{\mathbf{K}}_{-\Omega, h} + \left(\Psi^{-1} \gamma \right) \odot \left[\Psi^{-1} \left(\gamma \odot \left(b_h \Xi_{-\Omega, \Omega} \bar{\mathbf{K}}_{\Omega, h} + \boldsymbol{\zeta}_{1, -\Omega, h} \right) \right) \right]}_{=:\mathbf{q}_{-\Omega, \Omega, h}^{*-1}(\bar{\mathbf{K}}_h)}, \quad (34)$$

The function $\mathbf{q}_{A, B, h}^{*-1}(\mathbf{q}_h)$ returns the demand intercepts \mathbf{a}_h that would induce generators in A to produce \mathbf{q}_h , with generators in B producing their capacity constraints $\bar{\mathbf{K}}_{B, h}$.³⁹ The direction of the inequality depends on the sign of $\Psi^{-1} \gamma$. If $\Psi^{-1} \gamma$ is positive, the inequality will be \leq , and if $\Psi^{-1} \gamma$ is negative, the inequality will be \geq .

Now I need to define a function that maps the residual inverse demand intercept a_h to a set of constrained generators Ω . Consider a_h sufficiently small that the first condition holds for $\Omega_0 = \emptyset$.⁴⁰ Let $g_1 = \arg \min_{g \notin \Omega_0: [\Psi_0^{-1} \gamma_0]_g > 0} \left\{ \mathbf{q}_{-\Omega_0, \Omega_0, h}^{*-1}(\bar{\mathbf{K}}_h) \right\}$ and define $\Omega_1 = \{g_1\}$. $[\mathbf{x}]_i$ denotes the i th element of the vector \mathbf{x} . Note that generator g_1 is the tightest constraint and therefore the first to bind.⁴¹ I can now define the function $\Omega_h^* : \mathbb{R} \rightarrow \wp(\mathcal{G})$, mapping residual demand to constrained firms, recursively:

$$\begin{aligned} g_k &= \arg \min_{g \notin \Omega_{k-1}: [\Psi_{k-1}^{-1} \gamma_{k-1}]_g > 0} \left\{ \mathbf{q}_{-\Omega_{k-1}, \Omega_{k-1}, h}^{*-1}(\bar{\mathbf{K}}_h) \right\}, \\ a_k &= \min_{g \notin \Omega_{k-1}: [\Psi_{k-1}^{-1} \gamma_{k-1}]_g > 0} \left\{ \mathbf{q}_{-\Omega_{k-1}, \Omega_{k-1}, h}^{*-1}(\bar{\mathbf{K}}_h) \right\}, \\ \Omega_k &= \Omega_{k-1} \cup \{g_k\}, \end{aligned}$$

³⁹Note that this function returns a vector of demand intercepts \mathbf{a}_h , one for each generator in A . This is the demand intercept $a_{g, h}$ that would compel generator g to produce $q_{g, h}$ keeping other generators producing $\mathbf{q}_{-g, h}$.

⁴⁰Note that there always exists a sufficiently small a_h that this condition holds.

⁴¹I can ignore generators for which $\Psi_0^{-1} \gamma_0$ is less than 0. In this case, the quantity they produce is decreasing in a_h , and therefore their capacity constraints will not bind.

yielding⁴²

$$\Omega_h^*(a_h) = \begin{cases} \Omega_{0,h} & \text{if } a_h \in (-\infty, a_{1,h}] \\ \Omega_{1,h} & \text{if } a_h \in (a_{1,h}, a_{2,h}] \\ \vdots & \\ \Omega_{k,h} & \text{if } a_h \in (a_{n,h}, a_{n+1,h}] \\ \vdots & \\ \Omega_{G,h} & \text{if } a_h \in (a_{G,h}, \infty). \end{cases} \quad (35)$$

Note that $|\mathcal{G}| < |\varnothing(\mathcal{G})|$, so there are combinations of constrained firm-sources Ω that would not be supported by any $a_h \in \mathbb{R}$.

Note that I have not explicitly imposed the set of inequalities given by Equation 28. This is because for a generator g_k , the left hand side of Equation 28 implies that the optimal unconstrained quantity is increasing in a_h for any $a_h > a_k$. Intuitively, as I raise a_h , generators' capacity constraints begin to bind. As I continue to raise a_h , there are no constrained generators' for which capacity constraints that will cease to bind.

This fact is what allows me to determine Ω^* by solving for only (at most) G equilibria rather than 2^G equilibria, which becomes computationally infeasible beyond a small number of generators. I can therefore determine Ω^* recursively using the algorithm described above, then determine optimal (potentially constrained) quantities with generators $g \in \Omega_h^*$ operating at their capacity constraints.

C.1.2 Computing Equilibrium

Identifying Constrained Competitive Generators Up to this point I have presented the wholesale market model as if the residual demand curve that strategic firms face is linear. Since competitive firm generators also have capacity constraints, the residual demand curve is, in fact, piece-wise linear and convex, with kinks at points at which competitive generators'

⁴²Note that this function treats the arg min as a unique generator. In theory, multiple generators may constitute the arg min (altering the numbering of the intervals in $\Omega_h^*(\cdot)$); however, since costs $\zeta_{1,h}$ are drawn from a continuous distribution, this is a measure zero event, and therefore I do not consider this case in detail as it does not impact the final expected yearly wholesale profits.

capacity constraints bind. Specifically, the residual demand curve is given by

$$P_h(Q_h^{strategic}) = \begin{cases} a_{h,1} + b_{h,1}Q_h^{strategic} & \text{if } \bar{Q}_h - Q_h^{strategic} \in [\underline{q}_{h,c,1}, \bar{q}_{h,c,1}] \\ \vdots & \\ a_{h,k} + b_{h,k}Q_h^{strategic} & \text{if } \bar{Q}_h - Q_h^{strategic} \in (\underline{q}_{h,c,k}, \bar{q}_{h,c,k}] \\ \vdots & \\ a_{h,G_c} + b_{h,G_c}Q_h^{strategic} & \text{if } \bar{Q}_h - Q_h^{strategic} \in (\underline{q}_{h,c,G_c}, \bar{q}_{h,c,G_c}] \end{cases} \quad (36)$$

where \underline{q}_k and \bar{q}_k denote the quantities of the competitive firms that would yield a particular linear function, and G_c is the number of competitive generators the competitive firm owns. Note that $P_h(\cdot)$ is not defined for all $Q_h^{strategic}$. If there does not exist a (\underline{q}, \bar{q}) such that $\bar{Q} - Q^{strategic} \in [\underline{q}, \bar{q}]$, then the system experiences a blackout, and all firms receive zero profits for that period.

To compute the wholesale market equilibrium, I can therefore take the linear function extensions across the real line of each piece of the residual demand curve and compute the implied equilibrium based on strategic firms' decisions. I can then check whether that equilibrium implies that the competitive firm produces a quantity that is within the interval that would imply that linear demand curve. If it does, I consider it a *potential equilibrium*.

This process could yield one, many, or no potential equilibria. In the case of no potential equilibria, the system experiences a blackout. In the case of many potential equilibria, I must check whether all of the potential equilibria are indeed true equilibria. The set of first order conditions I use to find the equilibrium gives *local* maxima for the profit function, but each firm seeks to *globally* maximize its profit function. If a firm has the ability to choose a quantity that would move aggregate demand to a different piece of the demand curve, then its local maximum may not be its global maximum.

Being a potential equilibrium is therefore necessary but not sufficient for being an actual equilibrium. If there exists a potential equilibrium \mathbf{q}^* that is *dominated* by another potential equilibrium $\tilde{\mathbf{q}}^*$ —that is, $\pi_f(\mathbf{q}^*) < \pi_f(\tilde{\mathbf{q}}^*)$ for all strategic f —then the potential equilibrium \mathbf{q}^* is not, in fact, an equilibrium. I can therefore determine the set of equilibria by removing all dominated potential equilibria. Note that we may still have many equilibria; this process does not necessarily yield a unique one. In the case of multiple equilibria, I randomly choose an equilibrium.

Computing Distribution of Demand For a given distribution of demand Q_t , I can compute the distribution of prices, quantities and profits. To compute the yearly expected wholesale profit function, I perform the above described computation for a large number of

draws of the random variables of the model.⁴³ I then average over these draws to determine the expected wholesale profits.

The above allows me to compute the distribution of wholesale market variables conditional on a distribution of demand Q_t , but is an endogenous object that depends on wholesale prices. To compute the distribution of demand, I take an initial guess of average quantity-weighted wholesale prices \bar{P}_t^0 and compute the implied demand distribution and wholesale prices. I then update the quantity-weighted wholesale prices as follows. For a given quantity-weighted wholesale price \bar{P}_t^k ,

$$\bar{P}_t^{k+1} = \frac{1}{H} \sum_{h=1}^H \frac{\bar{Q}_h(\bar{P}_t^k) P_h(\bar{Q}_h(\bar{P}_t^k))}{\sum_{h=1}^H \bar{Q}_h(\bar{P}_t^k)},$$

where H is the number of draws of the wholesale market that I take. I then iterate on \bar{P}_t^k until convergence, i.e.

$$|\bar{P}_t^k - \bar{P}_t^{k-1}| < \varepsilon,$$

where ε is some threshold convergence tolerance (rather than cost shocks, as this letter represents in the main text).⁴⁴ This iteration until convergence (approximately) solves for the equilibrium condition given by equation 8. In practice, I find that convergence is quick, converging after just a few iterations.

C.1.3 Algorithm Summary

Algorithm 1 summarizes the algorithm described in this subsection, C.1.2. [UPDATE THE ALGORITHM TO REFLECT ITERATING ON DEMAND, CURRENTLY TREATS DEMAND AS EXOGENOUS]

C.2 Inverting Cost Shocks

Suppose we know which generators are constrained and which are not. I use the same notation as that introduced in section 4.1 in the main text to partition variables into those belonging to unconstrained generators and those belonging to constrained ones. The local competitive supply curve is given by equation 23. I can rewrite this equation locally as a function linear

⁴³Note that the algorithm, in contrast to the formula presented in the text, computes expected yearly wholesale profits *prior to taking into account capacity payments or maintenance costs*. Capacity payments (and associated expected penalties) and maintenance costs enter $\tilde{\Pi}$ additively, and can therefore be calculated separately and then added together.

⁴⁴I use a tolerance of $\varepsilon = 0.001$.

Algorithm 1: Compute $\Pi_t(\mathcal{G})$

Result: $\Pi_t(\mathcal{G})$

seed random number generator;

blackouts $\leftarrow 0$;**for** $h \leftarrow 1$ **to** H **do** sample $\bar{Q}_h, \delta_h, \zeta_{1,h}, \zeta_{2,h}$; convert $(\bar{Q}_h, \delta_h, \zeta_{1,h}, \zeta_{2,h})$ to $(\mathbf{a}_h, \mathbf{b}_h, \mathbf{q}_{h,c}, \bar{\mathbf{q}}_{h,c}, \bar{\mathbf{K}}_h)$; $\mathbf{q}_h^* \leftarrow \emptyset$; **for** $k \leftarrow 1$ **to** G_c **do** Omega_search \leftarrow true; $\Omega_{h,k} \leftarrow \emptyset$; $\ell_ctr \leftarrow 0$; **while** Omega_search **do** $g \leftarrow \arg \min \left\{ \mathbf{q}_{-\Omega_{h,k}, \Omega_{h,k}}^{*-1} \left(\bar{\mathbf{K}}_{-\Omega_{h,k}} \right) \right\}$; $a \leftarrow \min \left\{ \mathbf{q}_{-\Omega_{h,k}, \Omega_{h,k}}^{*-1} \left(\bar{\mathbf{K}}_{-\Omega_{h,k}} \right) \right\}$; **if** $a \geq a_{h,k}$ **then** Omega_search \leftarrow false; **else** $\Omega_{h,k} \leftarrow \Omega_{h,k} \cup \{g\}$; $\ell_ctr \leftarrow \ell_ctr + 1$; **end** **end** $\mathbf{q}_{h,k} \leftarrow \mathbf{q}_h^* (\Omega_{h,k})$; **if** $Q_h - \sum_{g \in \mathcal{G}} q_{g,h,k} \in [q_{h,c,k}, \bar{q}_{h,c,k}]$ **then** $\mathbf{q}_h^* \leftarrow \mathbf{q}_h^* \cup \mathbf{q}_{h,k}$; **end** **end** **if** $|\mathbf{q}_h^*| = 0$ **then** blackouts \leftarrow blackouts + 1; $\pi_h \leftarrow \mathbf{0}$; **else if** $|\mathbf{q}_h^*| = 1$ **then** $\pi_h \leftarrow \pi(\mathbf{q}_h^*; \zeta_{1,h}, \zeta_{2,h}, \bar{Q}_h)$; **else** $\mathbf{q}_h^* \leftarrow \left\{ \mathbf{q}_{h,k}^* \in \mathbf{q}_h^* : \nexists \mathbf{q}_{h,k'}^* \in \mathbf{q}_h^* \text{ s.t. } \pi_f(\mathbf{q}_{h,k'}^*) > \pi_f(\mathbf{q}_{h,k}^*) \forall f \in \mathcal{F}_{strategic} \right\}$; $\pi_h \leftarrow \frac{1}{K_h} \sum_k \pi(\mathbf{q}_{h,k}^*; \zeta_{1,h}, \zeta_{2,h}, \bar{Q}_h)$; **end** $\Pi \leftarrow \frac{1}{H} \sum_{h=1}^H \pi_h$; blackout_prob $\leftarrow \frac{\text{blackouts}}{H}$;**end**

in cost shocks as well as the market price:⁴⁵

$$Q_{c,h}(P_h) = \sum_{g \in \mathcal{G}_{c,h}^+} \bar{K}_{g,h} + \underbrace{\phi_h(\beta, \zeta_2) + \mathbf{c}_h(\zeta_2)' \boldsymbol{\varepsilon}_h^u}_{=\alpha_h} + \beta_h(\zeta_2) P_h, \quad (37)$$

where

$$\mathbf{c}_h(\zeta_2) = \begin{bmatrix} -\gamma_{1,h}(\zeta_{2,1}) & -\gamma_{2,h}(\zeta_{2,2}) & \dots & -\gamma_{g,h}(\zeta_{2,g}) & \dots & -\gamma_{G_{u,h},h}(\zeta_{2,G_{u,h}}) \end{bmatrix}',$$

where

$$\gamma_{g,h}(\zeta_{2,g}) = \begin{cases} \frac{1}{2\zeta_{2,g}K_g^{-2}} & \text{if } g \in \mathcal{G}_{c,h}^u \\ 0 & \text{otherwise,} \end{cases}$$

$$\phi_h(\beta, \zeta_2) = \sum_{g \in \mathcal{G}_h^u} -\gamma_{g,h}(\zeta_{2,1}) \beta'_{s(g)} \mathbf{x}_{g,h},$$

and

$$\beta_h(\zeta_2) = \sum_{g \in \mathcal{G}_h^u} \gamma_{g,h}(\zeta_{2,1}).$$

Plugging equation 37 into equation 24, the strategic residual demand curve is also linear:

$$P_h(Q_{s,h}) = \underbrace{\psi_h(\beta, \zeta_2) + \mathbf{d}_h(\beta, \zeta_2)' \boldsymbol{\varepsilon}_h^u}_{=a_h} - b_h(\zeta_2) Q_{s,h}, \quad (38)$$

where

$$\psi_h(\beta, \zeta_2) = \frac{\bar{Q}_h - Q_h^{\text{wind}} - \sum_{g \in \mathcal{G}_{c,h}^+} \bar{K}_{g,h} - \phi_h(\beta, \zeta_2)}{\beta_h(\zeta_2)},$$

$$\mathbf{d}_h(\beta, \zeta_2) = -\frac{1}{\beta_h(\zeta_2)} \mathbf{c}_h(\zeta_2),$$

and

$$b_h(\zeta_2) = \frac{1}{\beta_h(\zeta_2)}.$$

Given the demand curve, equation 26 provides a formula for the equilibrium strategic firms' production decisions:

$$\mathbf{q}_{s,h}^u = \mathbf{E}_h(\beta, \zeta_2) \boldsymbol{\varepsilon}_h^u + \mathbf{f}_h(\beta, \zeta_2), \quad (39)$$

where

$$\mathbf{E}_h(\beta, \zeta_2) = \boldsymbol{\Psi}_h(\zeta_2)^{-1} \left[\frac{1}{2b_h(\zeta_2) \mathbf{1}_{G_{s,h}^u} + 2\zeta_{2,s} \odot \mathbf{K}^{u \odot -2} \mathbf{1}_{G_h^u}'} \odot \left(\mathbf{1}_{G_{s,h}^u} \mathbf{d}_h(\beta, \zeta_2)' - [I_{G_h^u}]_{\mathcal{G}_{s,h}^u} \right) \right],$$

⁴⁵ *Locally* mean a neighborhood in which the constrained generators remain constrained.

and

$$\mathbf{f}_h(\beta, \zeta_2) = \Psi_h(\zeta_2)^{-1} \left[\frac{1}{2b_h(\zeta_2) \mathbf{1}_{G_{s,h}^u} + 2\zeta_{2,s}^u \odot \mathbf{K}^{u \circ -2}} \odot \left(\psi_h(\beta, \zeta_2) \mathbf{1}_{G_{s,h}^u} - b_h(\zeta_2) \Xi_{\mathcal{G}_{s,h}^u, \mathcal{G}_{s,h}^+} \bar{\mathbf{K}}_{s,h}^+ - \mathbf{X}_{s,h}^u \beta \right) \right],$$

where division is element-wise, $\mathbf{a}^{\circ 2}$ is the vector \mathbf{a} squared element-wise, and

$$\Psi_h(\zeta_2) = I_{G_{s,h}^u} + \frac{b_h(\zeta_2) \mathbf{1}_{G_{s,h}^u}}{2b_h(\zeta_2) \mathbf{1}_{G_{s,h}^u} + 2\zeta_{2,s}^u \odot \mathbf{K}^{u \circ -2}} \mathbf{1}_{G_{s,h}^u}' \odot \Xi_{\mathcal{G}_{s,h}^u, \mathcal{G}_{s,h}^+}.$$

Plugging equation 39 into equation 38, we get a formula for prices as a function of cost shocks:

$$P_h = \mathbf{g}_h(\beta, \zeta_2)' \varepsilon_h^u + j_h(\beta, \zeta_2), \quad (40)$$

where

$$\mathbf{g}_h(\beta, \zeta_2) = \mathbf{d}_h(\beta, \zeta_2) - b_h(\zeta_2) \mathbf{E}_h(\beta, \zeta_2)' \mathbf{1}_{G_{s,h}^u}$$

and

$$j_h(\beta, \zeta_2) = \psi_h(\beta, \zeta_2) - b_h \left((\zeta_2) \mathbf{1}_{G_{s,h}^u}' \mathbf{f}_h(\beta, \zeta_2) + \sum_{g \in \mathcal{G}_{s,h}^+} \bar{K}_{g,h} \right).$$

Using the fact that for competitive generator g , $q_{g,h} = \frac{P_h - \beta_{s(g)}' \mathbf{x}_{g,h} - \varepsilon_{g,h}}{2\zeta_{2,s(g)} K_g^{-2}}$, we have

$$\mathbf{q}_{c,h}^u = \mathbf{K}_h(\beta, \zeta_2) \varepsilon_h^u + \ell_h(\beta, \zeta_2),$$

where

$$\mathbf{K}_h(\beta, \zeta_2) = \frac{1}{2\zeta_{2,c,h}^u \odot \mathbf{K}_c^{u \circ -2}} \mathbf{1}_{G_h^u}' \odot \left(\mathbf{1}_{G_{c,h}^u} \mathbf{g}_h(\beta, \zeta_2)' - [I_{G_h^u}]_{\mathcal{G}_{c,h}^u, \cdot} \right)$$

and

$$\ell_h(\beta, \zeta_2) = \frac{1}{2\zeta_{2,c,h}^u \odot \mathbf{K}_c^{u \circ -2}} \odot \left(j_h(\beta, \zeta_2) \mathbf{1}_{G_{c,h}^u} - \mathbf{X}_{c,h}^u \beta \right).$$

Therefore, I can combine the expressions for $\mathbf{q}_{c,h}^u$ and $\mathbf{q}_{s,h}^u$, which yields

$$\mathbf{q}_h^u = \mathbf{M}_h(\beta, \zeta_2) \varepsilon_h^u + \mathbf{n}_h(\beta, \zeta_2), \quad (41)$$

where

$$\mathbf{M}_h(\beta, \zeta_2) = \begin{bmatrix} \mathbf{m}_{1,h}(\beta, \zeta_2) \\ \mathbf{m}_{2,h}(\beta, \zeta_2) \\ \vdots \\ \mathbf{m}_{g,h}(\beta, \zeta_2) \\ \vdots \\ \mathbf{m}_{G_h^u,h}(\beta, \zeta_2) \end{bmatrix} \quad \text{and} \quad \mathbf{n}_h(\beta, \zeta_2) = \begin{bmatrix} n_{1,h}(\beta, \zeta_2) \\ n_{2,h}(\beta, \zeta_2) \\ \vdots \\ n_{g,h}(\beta, \zeta_2) \\ \vdots \\ n_{G_h^u,h}(\beta, \zeta_2) \end{bmatrix},$$

where

$$\mathbf{m}_{g,h}(\beta, \zeta_2) = \begin{cases} [\mathbf{K}_h(\beta, \zeta_2)]_g, & \text{if } g \in \mathcal{G}_{c,h}^u \\ [\mathbf{E}_h(\beta, \zeta_2)]_g, & \text{if } g \in \mathcal{G}_{s,h}^u \end{cases}$$

and

$$n_{g,h}(\beta, \zeta_2) = \begin{cases} [\ell_h(\beta, \zeta_2)]_g & \text{if } g \in \mathcal{G}_{c,h}^u \\ [\mathbf{f}_h(\beta, \zeta_2)]_g & \text{if } g \in \mathcal{G}_{s,h}^u. \end{cases}$$

Now I show that we can invert the quantities \mathbf{q}_h^u and the price P_h to obtain the vector of cost shocks for unconstrained generators $\boldsymbol{\varepsilon}_h^u$. While the dimension \mathbf{q}_h^u is the same as that of $\boldsymbol{\varepsilon}_h^u$, we cannot simply invert equation 41 in order to recover $\boldsymbol{\varepsilon}_h^u$. The rank of $\mathbf{M}_h(\beta, \zeta_2)$ is one less than its dimension (i.e., $\text{rank}(\mathbf{M}_h(\beta, \zeta_2)) = |\mathbf{q}_h^u| - 1$). The equilibrium is constructed such that the sum of generators' quantities is equal to \bar{Q}_h . Intuitively, the “final” quantity is not independent; it is a linear function of the others' quantities.

By using information on the realized price, P_h , however, I can still recover the vector $\boldsymbol{\varepsilon}_h^u$. Specifically, I remove a row i in \mathbf{q}_h^u , $\mathbf{M}_h(\beta, \zeta_2)$, and $\mathbf{n}_h(\beta, \zeta_2)$ that is linearly dependent in $\mathbf{M}_h(\beta, \zeta_2)$. I then replace row i with P_h , $\mathbf{g}_h(\beta, \zeta_2)'$, and $j_h(\zeta_2)$, respectively. Let's call the new vectors/matrices $\tilde{\mathbf{q}}_h^u$, $\tilde{\mathbf{M}}_h(\beta, \zeta_2)$, and $\tilde{\mathbf{n}}_h(\beta, \zeta_2)$, respectively. The matrix $\tilde{\mathbf{M}}_h(\beta, \zeta_2)$ is full rank and therefore invertible. I can therefore solve for $\boldsymbol{\varepsilon}_h^u$ as follows:

$$\boldsymbol{\varepsilon}_h^u(\mathbf{q}_h^u, P_h; \beta, \zeta_2) = \tilde{\mathbf{M}}_h(\beta, \zeta_2)^{-1} (\tilde{\mathbf{q}}_h^u - \tilde{\mathbf{n}}_h(\beta, \zeta_2)). \quad (42)$$

C.3 Wholesale Market Log-likelihood

In order to compute the likelihood given in equation 16, I need to determine a tractable way to compute $\Pr(\boldsymbol{\varepsilon}_h^+ \geq \boldsymbol{\nu}_h^+ \text{ and } \boldsymbol{\varepsilon}_h^- \leq \boldsymbol{\nu}_h^- \mid \boldsymbol{\varepsilon}_h^u = \mathbf{e}_h^u; \boldsymbol{\Sigma}_\varepsilon)$. Note that the conditional distribution of a subset of the components of a multivariate normal, conditioning on the other elements, is also normal:

$$\boldsymbol{\varepsilon}_h^{-u} \mid \boldsymbol{\varepsilon}_h^u = \mathbf{e}_h^u \sim \mathcal{N}(\tilde{\boldsymbol{\mu}}_\varepsilon(\mathbf{e}_h^u), \tilde{\boldsymbol{\Sigma}}_\varepsilon(\mathbf{e}_h^u)),$$

where

$$\tilde{\boldsymbol{\mu}}_{\boldsymbol{\varepsilon}}(\mathbf{e}_h^u) = \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{-u,u} (\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{u,u})^{-1} \mathbf{e}_h^u$$

and

$$\tilde{\boldsymbol{\Sigma}}_{\boldsymbol{\varepsilon}}(\mathbf{e}_h^u) = \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{-u,-u} - \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{-u,u} (\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{u,u})^{-1} \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}^{u,-u}.$$

Therefore,

$$\Pr\left(\boldsymbol{\varepsilon}_h^+ \leq \boldsymbol{\nu}_h^+ \text{ and } \boldsymbol{\varepsilon}_h^- \geq \boldsymbol{\nu}_h^- \mid \boldsymbol{\varepsilon}_h^u = \mathbf{e}_h^u, \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}\right) = \Pr\left(\boldsymbol{\varepsilon}_h^+ \leq \boldsymbol{\nu}_h^+ \text{ and } \boldsymbol{\varepsilon}_h^- \geq \boldsymbol{\nu}_h^-; \tilde{\boldsymbol{\mu}}_{\boldsymbol{\varepsilon}}(\mathbf{e}_h^u), \tilde{\boldsymbol{\Sigma}}_{\boldsymbol{\varepsilon}}(\mathbf{e}_h^u)\right).$$

Therefore, equation 16 can be rewritten as

$$\begin{aligned} \ell(\boldsymbol{\beta}, \boldsymbol{\zeta}_2, \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}) &= \sum_h \log\left(\phi_{G_h^u}(\boldsymbol{\varepsilon}_h^u(\boldsymbol{\beta}, \boldsymbol{\zeta}_2); \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}})\right) \\ &\quad + \log\left(\Phi_{G_h^{-u}}\left(\boldsymbol{\nu}_h^{-u}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2), \bar{\boldsymbol{\nu}}_h^{-u}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2); \tilde{\boldsymbol{\mu}}_{\boldsymbol{\varepsilon}}(\boldsymbol{\varepsilon}_h^u(\boldsymbol{\beta}, \boldsymbol{\zeta}_2)), \tilde{\boldsymbol{\Sigma}}_{\boldsymbol{\varepsilon}}(\boldsymbol{\varepsilon}_h^u(\boldsymbol{\beta}, \boldsymbol{\zeta}_2))\right)\right), \end{aligned} \quad (43)$$

where

$$\Phi_k(\mathbf{a}, \mathbf{b}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) = \int_{a_1}^{b_1} \dots \int_{a_k}^{b_k} \phi_k(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) d\mathbf{x}$$

and

$$\boldsymbol{\nu}_h^{-u}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) = \begin{bmatrix} \nu_{1,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \\ \vdots \\ \nu_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \\ \vdots \\ \nu_{G_h^{-u},h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \end{bmatrix} \quad \text{and} \quad \bar{\boldsymbol{\nu}}_h^{-u}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) = \begin{bmatrix} \bar{\nu}_{1,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \\ \vdots \\ \bar{\nu}_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \\ \vdots \\ \bar{\nu}_{G_h^{-u},h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) \end{bmatrix},$$

where

$$\nu_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) = \begin{cases} \nu_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) & \text{if } g \in \mathcal{G}_h^- \\ -\infty & \text{if } g \in \mathcal{G}_h^+. \end{cases} \quad \text{and} \quad \bar{\nu}_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) = \begin{cases} \infty & \text{if } g \in \mathcal{G}_h^- \\ \nu_{g,h}(\boldsymbol{\beta}, \boldsymbol{\zeta}_2) & \text{if } g \in \mathcal{G}_h^+ \end{cases}$$

Note that equation 43 requires computing

$$\Phi_{G_h^{-u}}\left(\boldsymbol{\nu}_h^{-u}, \bar{\boldsymbol{\nu}}_h^{-u}; \tilde{\boldsymbol{\mu}}_{\boldsymbol{\varepsilon}}, \tilde{\boldsymbol{\Sigma}}_{\boldsymbol{\varepsilon}}\right). \quad (44)$$

This integral has no closed form solution and is numerically difficult to compute. In order to approximate the integral given in equation 44, I first decompose the the covariance matrix in order to obtain the correlation matrix, as follows:

$$\tilde{\boldsymbol{\Sigma}}_{\boldsymbol{\varepsilon}} = \mathbf{D}\mathbf{R}\mathbf{D}',$$

where \mathbf{D} is the diagonal matrix

$$\mathbf{D} = \begin{bmatrix} \sigma_1 & & & & & \\ & \ddots & & & & \\ & & \mathbf{0} & & & \\ & & & \sigma_g & & \\ & \mathbf{0} & & & \ddots & \\ & & & & & \sigma_{G_h^{-u}} \end{bmatrix} \quad \text{and} \quad \mathbf{R} = \begin{bmatrix} 1 & \rho_{1,2} & \cdots & \rho_{1,g} & \cdots & \rho_{1,G} \\ \rho_{2,1} & 1 & & & & \ddots \\ \vdots & & \ddots & & & \\ \rho_{g,1} & & & 1 & & \\ \vdots & \ddots & & & \ddots & \\ \rho_{G,1} & & & & & 1 \end{bmatrix}.$$

Then

$$\Phi_{G_h^{-u}}(\boldsymbol{\nu}_h^{-u}, \bar{\boldsymbol{\nu}}_h^{-u}, \tilde{\boldsymbol{\mu}}_\varepsilon, \tilde{\boldsymbol{\Sigma}}_\varepsilon) = \Phi_{G_h^{-u}}(\mathbf{a}, \mathbf{b}; \mathbf{R}),$$

where $\Phi_k(\cdot, \cdot; \cdot)$ is the standardized analogue of $\Phi_k(\cdot, \cdot; \cdot, \cdot)$ and

$$\mathbf{a} = \mathbf{D}^{-1}(\boldsymbol{\nu}_h^{-u} - \tilde{\boldsymbol{\mu}}_\varepsilon) \quad \text{and} \quad \mathbf{b} = \mathbf{D}^{-1}(\bar{\boldsymbol{\nu}}_h^{-u} - \tilde{\boldsymbol{\mu}}_\varepsilon).$$

I next note that the structure placed on $\rho_{g,g'}$ allows me to use a useful transformation to transform equation 44 from a G_h^{-u} -dimensional integral to a lower-dimensional one. [Genz & Bretz \(2009\)](#) show that if a correlation matrix has a reduced rank of ℓ ,⁴⁶ as the correlation matrix does,⁴⁷ then the multivariate integral has the following simplified form:

$$\Phi_k(\mathbf{a}, \mathbf{b}; \mathbf{R}) = \int_{\mathbb{R}^\ell} \phi_\ell(\mathbf{y}; \mathbf{I}_\ell) \prod_{i=1}^k \left(\Phi\left(\frac{b_i - \sum_{j=1}^\ell v_{ij} y_j}{\sqrt{d_i}}\right) - \Phi\left(\frac{a_i - \sum_{j=1}^\ell v_{ij} y_j}{\sqrt{d_i}}\right) \right) d\mathbf{y}, \quad (45)$$

where $\Phi(\cdot)$ is the one-dimensional c.d.f. of the standard normal.

I can then approximate the integral given in equation 45 using Gauss-Hermite quadrature:

$$\Phi_k(\mathbf{a}, \mathbf{b}; \mathbf{R}) \approx \pi^{-\ell/2} \sum_{k_1=1}^{n_1} \cdots \sum_{k_\ell=1}^{n_\ell} \left(\prod_{\ell} w_{\ell, k_\ell} \right) \prod_{i=1}^k \left(\Phi\left(\frac{b_i - \sqrt{2} \sum_{j=1}^\ell v_{i,j} x_{j, k_j}}{\sqrt{d_i}}\right) - \Phi\left(\frac{a_i - \sqrt{2} \sum_{j=1}^\ell v_{i,j} x_{j, k_j}}{\sqrt{d_i}}\right) \right),$$

where x_{ℓ, k_ℓ} is a sample point with associated weight w_{ℓ, k_ℓ} for dimension ℓ .

In the case of the multivariate integral I must compute (equation 44), $\ell = 2$, yielding a feasible method of computing the multivariate integral.

⁴⁶A correlation matrix \mathbf{R} exhibits a *reduced rank* of ℓ if $\mathbf{R} = \mathbf{D} + \mathbf{V}\mathbf{V}'$ where \mathbf{D} is a diagonal matrix with nonzero entries d_i along the diagonal, and \mathbf{V} is a $k \times \ell$ matrix, where $\ell < k$.

⁴⁷The matrix $\boldsymbol{\Sigma}_\varepsilon$ has a reduced rank because the correlation in generators comes solely through the generator energy source. Since $\boldsymbol{\Sigma}_\varepsilon$ has this reduced rank, $\tilde{\boldsymbol{\Sigma}}_\varepsilon$ also has the same reduced rank, according to Corollary 3.1 in Appendix F.

C.4 Construction of Γ

Due to computational constraints, I must restrict the set of possible generator combinations, Γ , in two ways: the size of the generators and the number of generators. While estimation of the wholesale market allows for heterogeneous generators within a source (e.g., a coal generator of size 100 MW and one of size 200 MW), I will restrict all generators in Γ to be of some representative size for each energy source, provided in table 11. The reason I limit generators to be of a particular size is to avoid determining which generators to retire or add. If I allowed all of the different sizes of generators that I observe in the data (or that a firm might theoretically build), then each firm would decide not only how many generators to have at a given time, but which of the many sizes to have. Allowing for heterogeneous generators (apart from the energy source) creates an extremely large number of possible combinations. For example, there are 8 different sizes of coal generators if I round to the nearest 10 MW. Assuming I don't allow for any heterogeneity in sizes apart from those observed in the data, a firm with the ability to build up to N coal generators would have as its set of possible options not $N + 1$ options but $\frac{(8+N-1)!}{N!(8-1)!}$ options. This is a large number, but it is also only one firm and one energy source. When I consider that I must consider all firms and all energy sources, the number is clearly computationally intractable. I therefore assume all generators of a particular source are identical.

Table 11: Representative Generator Sizes

source	generator size (in MW)
coal	200
gas	100
wind	50

The second restriction I must make is with respect to the number of generators. Ideally, I would allow for the set of possible generators a firm could build of a particular source to be $\{0, 1, \dots, N\}$, where N is a very high number. While I do not have the combinatorial problem outlined above when I assume generators of a particular source are homogenous in size, this fine grid of generator combinations becomes intractably large when I consider all combinations across firm and energy sources. The state space is created as follows

$$\Gamma = \prod_{f \in \{1, \dots, N, c\}} \times \prod_{s \in \mathcal{S}} \Gamma_{f,s},$$

where $\Gamma_{f,s}$ is the uni-dimensional grid of possible generators. If N were 30, with three strategic firms, I would have a state space of size $(N + 1)^{4 \times |\mathcal{S}|} \approx 7.9 \times 10^{17}$, an intractably large number for computing the equilibrium. I therefore use a much sparser set of generator combinations in each $\Gamma_{f,s}$, where the grid is chosen to include generator combinations observed in the data,

as well as some above and below. Sources that a firm never chooses to use are assumed to not be available to that firm (e.g., firm 1 (WPGENER) has virtually no wind generators, so I set $\Gamma_{f,s} = [0]$). Table 12 lists the set of possible generators $\Gamma_{f,s}$ for each firm and energy source. With this set of generators, the size of the state space $|\Gamma| = 155\,520$.

Table 12: Γ used in Estimation

f	s	$\Gamma_{f,s}$
1	coal	[2, 4, 6, 8, 10, 12]
1	gas	[15, 16, 17, 18, 19, 20]
1	wind	[0]
2	coal	[0]
2	gas	[5, 7, 9, 11]
2	wind	[0, 4, 8, 12]
3	coal	[0, 2, 4]
3	gas	[0]
3	wind	[0]
c	coal	[0, 1, 2]
c	gas	[2, 4, 6, 8, 10]
c	wind	[0, 2, 6, 10, 14, 18]

Of course, in the data there are heterogeneous generators. I therefore must match heterogeneous generator sets in the data to sets with homogeneous generators. Rather than simply counting the number of generators, I determine which state the data corresponds to in each period in the following way. I first add up the capacities of all of the generators for each firm and energy source, $K_{f,s,t}$. I then determine the number of energy homogeneous generators, $G_{f,s,t}$, that would yield $K_{f,s,t}$, i.e.

$$G_{f,s,t} = \frac{K_{f,s,t}}{K_s},$$

where K_s is the generator size from table 11.

In my counterfactuals, I explore policies that may cause investment patterns to look very different. I therefore use a more expansive grid of possible generator combinations. For estimation, the goal in choosing $\Gamma_{f,s}$ was to have a sufficiently fine Γ that I could track changes to generator levels observed in the data. In counterfactuals, the imposition of a carbon tax might, for example, substantially increase the level of wind investment. I therefore use the grid given in table 13 as that state space for the counterfactuals, which is more expansive, but also sparser. Similarly to estimation, I restrict the sources in which strategic firms can invest. I use the same restriction as in the estimation (e.g., firm 1 can only invest in wind), but I allow firm 3 to also invest in wind. This creates three firms, each of which can invest in only two sources, and no two firms can invest in the same two sources. I use the same $\Gamma_{f,s}$ for each s , i.e., $\Gamma_{f,s} = \Gamma_s$. The size of the state space for the counterfactuals, $|\Gamma|$, is therefore

196 608.

Table 13: Γ used in Counterfactuals

f	s	$\Gamma_{f,s}$
1	coal	[0, 3, 6, 10]
1	gas	[5, 11, 18, 25]
1	wind	[0]
2	coal	[0]
2	gas	[5, 11, 18, 25]
2	wind	[0, 10, 20, 30]
3	coal	[0, 3, 6, 10]
3	gas	[0]
3	wind	[0, 10, 20, 30]
c	coal	[0, 3, 6, 10]
c	gas	[5, 11, 18, 25]
c	wind	[0, 10, 20, 30]

In determining the initial state in which the counterfactuals begin, I use the state observed in the first year of the data. To determine which state in table 13 corresponds to that observed in the data, I use the same method of determining the state as that described above for estimation.

C.5 Model of $\mathcal{G}_t^*(\cdot)$ and Computation

I assume that the competitive fringe can only adjust one energy source in a year, and this energy source is randomly chosen. This assumption is made for the following reasons. First, since only one strategic firm can move in a period, this restricts the competitive fringe from having an advantage over strategic firms simply due to the timing assumptions. Second, in the data, it is never the case that more than one energy source in the competitive fringe adjusts in a given year.

The equilibrium set of generators after competitive entry, conditional on the source s being chosen to adjust, is given by

$$\mathcal{G}_t^*(\mathcal{G}, \boldsymbol{\eta}_c, s) = \underbrace{\mathcal{G}_{s,t}}_{\text{existing strategic generators}} \cup \underbrace{\mathcal{G}_{c,-s,t}}_{\text{existing competitive generators of source } s' \neq s} \cup \underbrace{\mathcal{G}_{c,s,t}^*(\mathcal{G}, \boldsymbol{\eta}_{c,s})}_{\text{set of competitive generators of source } s \text{ after adjustment decisions}},$$

where $\mathcal{G}_{c,s,t}^*(\mathcal{G}, \boldsymbol{\eta}_{c,s})$ is the set of competitive generators that belong to energy source s after

generator entry and retirements in year t . Explicitly,

$$\mathcal{G}_{c,s,t}^* (\mathcal{G}, \boldsymbol{\eta}_{c,s}) = \mathcal{G}_{c,s,t}^R (\mathcal{G}, \boldsymbol{\eta}_{c,s}) \cup \mathcal{G}_{c,s,t}^E (\mathcal{G}, \boldsymbol{\eta}_{c,s}),$$

where $\mathcal{G}_{c,s,t}^R (\mathcal{G}, \boldsymbol{\eta}_{c,s})$ is the set of competitive generators of source s that were already in the market in period $t - 1$ and choose to remain in the market in period t , and $\mathcal{G}_{c,s,t}^E (\mathcal{G}, \boldsymbol{\eta}_{c,s})$ is the set of potential entrant competitive generators of source s that choose to enter into the market in period t .

These two sets are determined in two stages. In a first stage, the existing generators in $\mathcal{G}_{c,s}$ make retirement decisions, and in a second stage potential entrant competitive generators belonging to source s make entry decisions. Existing generators make retirement decisions by comparing the value of remaining in the market and leaving the market, taking an expectation over the potential entrants' entry decisions. The potential entrants observe the existing generators' retirement decisions and then proceed to make entry decisions.

In each stage, a generator will enter if the value of being in the market in period t exceeds the value of being out of the market in that period, where the value is defined by equation 12. Since there is no heterogeneity in generators belonging to the same source and firm, we can reduce the sets $\mathcal{G}_{c,s,t}^R$ and $\mathcal{G}_{c,s,t}^E$ to integers $G_{c,s,t}^R$ and $G_{c,s,t}^E$, respectively, corresponding to the number of generators in the set.⁴⁸ Let $\mathcal{G}^R (G_{c,s,t}^R)$ and $\mathcal{G}^E (G_{c,s,t}^E)$ convert the integer values back into generator sets.

For each of these stages, I can then define $\bar{\eta}_{s,t} (G)$ as value for which if $\eta_{g,\text{in},t} - \eta_{g,\text{out},t} \geq \bar{\eta}_{s,t} (G)$, then a generator would choose to be in the market in period t in which there are G competitive generators of source s (either entering or remaining depending on the stage), and the set of generators \mathcal{G} are already in the market prior to the firm's entry or remaining decisions. Explicitly,

$$\begin{aligned} \bar{\eta}_{s,t}^R (G^R) &= \mathbb{E} \left[v_{s,t}^{\text{out}} \left(\text{in}, \mathcal{G}_{s,t} \cup \mathcal{G}_{c,-s,t} \cup \mathcal{G}^R (G^R) \cup \mathcal{G}^E (G_{c,s,t}^E (G^R, \boldsymbol{\eta}_{c,s,t})) \right) \right] \\ &\quad - \mathbb{E} \left[v_{s,t}^{\text{in}} \left(\text{in}, \mathcal{G}_{s,t} \cup \mathcal{G}_{c,-s,t} \cup \mathcal{G}^R (G^R) \cup \mathcal{G}^E (G_{c,s,t}^E (G^R, \boldsymbol{\eta}_{c,s,t})) \right) \right] \\ \bar{\eta}_{s,t}^E (G^E) &= v_{s,t}^{\text{out}} \left(\text{out}, \mathcal{G}_{s,t} \cup \mathcal{G}_{c,-s,t} \cup \mathcal{G}_{c,s,t}^R \cup \mathcal{G}^E (G^E) \right) \\ &\quad - v_{s,t}^{\text{in}} \left(\text{out}, \mathcal{G}_{s,t} \cup \mathcal{G}_{c,-s,t} \cup \mathcal{G}_{c,s,t}^R \cup \mathcal{G}^E (G^E) \right). \end{aligned}$$

The first definition represents the cutoff value for generators currently in the market (hence, the first argument of each value function denotes a generator currently in the market). Note that the values of remaining in the market or exiting are expected values, where the expecta-

⁴⁸ As detailed in section C.4, for computational reasons in practice I cannot use a grid of integers $0, 1, \dots, \bar{G}$, and instead use a coarser grid, e.g., $0, G, 2G, \dots, \bar{G}$. In practice, I assume that each group of generators (e.g., $1, 2, \dots, G$) draw the same $(\eta_{g,\text{in},t}, \eta_{g,\text{out},t})$.

tion is taken over what potential entrants will do. The second definition represents the cutoff value for potential entrant generators (captured again by the first argument in the value functions). Unlike the generators currently in the market, they do not take an expectation since profits are realized immediately following their entry decisions.

I assume that in both stages, the generator with the highest $\eta_{g,\text{in},t} - \eta_{g,\text{out},t}$ makes its decision first, then the generator with the next highest, and so on until all existing or potential entrant generators have decided whether to be in the market or out of it in period t . Let $\eta_{g,t}^{\text{diff}} = \eta_{g,\text{in},t} - \eta_{g,\text{out},t}$. This timing implies that a generator need only consider its realized cost shocks when it makes its decision of whether to be in the market, not any of the other generators making decisions at the same stage. The values $\bar{\eta}_{s,t}^R(G^R)$ and $\bar{\eta}_{s,t}^E(G^E)$ are increasing in G^R and G^E , respectively.⁴⁹ When a generator makes its decision to be in the market, it observes the number of generators in the market G based on the decisions within the stage made before its turn. A generator need only consider the value of being in the market with G generators, since all generators following it have lower values of $\eta_{g,t}^{\text{diff}}$. If a generator following it also decides to be in the market, then it would be profitable for the generator in question to remain in the market.

For simplicity, index generators from lowest to highest $\eta_{g,t}^{\text{diff}}$. The condition yielding G^R or G^E in equilibrium is therefore given by the following, where I drop s and t subscripts for notational simplicity:

$$\eta_g^{\text{diff}} \geq \bar{\eta}^e(G^e) \forall g > \bar{G}^e - G^e \quad \text{and} \quad \eta_g^{\text{diff}} < \bar{\eta}^e(G^e + 1) \forall g \leq \bar{G}^e - G^e \quad \text{for } e \in \{R, E\},$$

where \bar{G}^e corresponds to the number of existing generators (in the case of R) or the number of potential entrants (in the case of E). Note that this is equivalent to

$$\eta_{(\bar{G}^e - G^e + 1)}^{\text{diff}} \geq \bar{\eta}^e(G^e) \quad \text{and} \quad \eta_{(\bar{G}^e - G^e)}^{\text{diff}} < \bar{\eta}^e(G^e + 1) \quad \text{for } e \in \{R, E\},$$

where $\eta_{(i)}^{\text{diff}}$ corresponds to the i th order statistic out of \bar{G}^e .

The probabilities of a particular set of existing or potential entrant competitive generators belonging to source s being in the market in period t is therefore given by

$$\begin{aligned} & \Pr\left(\left|\mathcal{G}_{c,s,t}^e(\mathcal{G}, \boldsymbol{\eta}_{c,s})\right| = G\right) \\ &= \Pr\left(\eta_{(\bar{G}^e - G + 1)}^{\text{diff}} \geq \bar{\eta}^e(G) \text{ and } \eta_{(\bar{G}^e - G)}^{\text{diff}} \geq \bar{\eta}^e(G + 1)\right) \\ &= \int_{\bar{\eta}^e(G)}^{\infty} \int_{-\infty}^{\bar{\eta}^e(G+1)} \frac{\bar{G}^e!}{(\bar{G}^e - G - 1)!(G - 1)!} F\left(\eta_{\bar{G}^e - G}^{\text{diff}}\right)^{\bar{G}^e - G - 1} \left(1 - F\left(\eta_{\bar{G}^e - G + 1}^{\text{diff}}\right)\right)^{G - 1} \\ & \quad \cdot f\left(\eta_{\bar{G}^e - G}^{\text{diff}}\right) f\left(\eta_{\bar{G}^e - G + 1}^{\text{diff}}\right) \mathbb{1}\left\{\eta_{\bar{G}^e - G + 1}^{\text{diff}} > \eta_{\bar{G}^e - G}^{\text{diff}}\right\} d\eta_{\bar{G}^e - G}^{\text{diff}} d\eta_{\bar{G}^e - G + 1}^{\text{diff}}, \end{aligned}$$

⁴⁹See Appendix F for a proof of this claim.

where $F(\cdot)$ is the c.d.f. of the distribution of η . Evaluating this integral yields the following closed form solution

$$\Pr\left(\left|\mathcal{G}_{c,s,t}^e(\mathcal{G}, \boldsymbol{\eta}_{c,s})\right| = G\right) = \frac{\phi(G, \bar{G}^e)}{\bar{G}^e - G} \left(B_{F(\bar{\eta}^e(G+1))}(\bar{G}^e - G + 1, G) - B_{F(\bar{\eta}^e(G))}(\bar{G}^e - G + 1, G) \right) + \frac{\phi(G, \bar{G}^e)}{G(\bar{G}^e - G)} F(\bar{\eta}^e(G+1))^{\bar{G}^e - G} (1 - F(\bar{\eta}^e(G+1)))^G,$$

where $\phi(G, \bar{G}^e) = \frac{\bar{G}^e!}{(\bar{G}^e - G - 1)!(G - 1)!}$ and $B(\cdot, \cdot)$ is the incomplete Beta function.⁵⁰ Note that I assume $\eta \sim \text{T1EV}(\sigma)$, where σ is the scaling parameter, so

$$F(\bar{\eta}) = \frac{\exp(\bar{\eta}/\sigma)}{1 + \exp(\bar{\eta}/\sigma)}.$$

D Additional Results

[NEED TO ADD]

E Robustness Checks

E.1 Capacity Imputations

[NEED TO ADD THE CAPACITY IMPUTATION CHECKS I DID]

F Proofs

Proposition 2. *There exists a unique $\Omega \in \wp(\mathcal{G})$ such that all inequalities in Equations 27 and 28 hold.*

Proof. TBA. □

Proposition 3. *If the covariance matrix $\boldsymbol{\Sigma}$ has a reduced rank of ℓ , then its Schur complement also has a reduced rank of (at most) ℓ .*

Proof. Partition $\boldsymbol{\Sigma}$ into $\boldsymbol{\Sigma} = \begin{bmatrix} \boldsymbol{\Sigma}_{11} & \boldsymbol{\Sigma}_{12} \\ \boldsymbol{\Sigma}_{21} & \boldsymbol{\Sigma}_{22} \end{bmatrix}$, where $\boldsymbol{\Sigma}_{11}$ and $\boldsymbol{\Sigma}_{22}$ are square matrices. By

⁵⁰The incomplete Beta function is defined as $B_x(a, b) = \int_0^x u^{a-1} (1-u)^{b-1} du$.

assumption, Σ has a reduced rank of ℓ , which by definition means

$$\Sigma = \mathbf{F} [\mathbf{D} + \mathbf{V}\mathbf{V}'] \mathbf{F},$$

where \mathbf{F} is a diagonal matrix with standard deviations along the diagonal, \mathbf{D} is a diagonal matrix with values $d_i = 1 - \mathbf{v}_{i,\cdot} \mathbf{v}'_{i,\cdot}$ along the diagonal, and \mathbf{V} is a $k \times \ell$ matrix. These variables are functions of Σ , but, for the sake of space, I omit the dependence in the notation. I can partition \mathbf{F} , \mathbf{D} , and the rows of \mathbf{V} analogously to Σ .⁵¹ Then,

$$\begin{aligned} \Sigma_{ij} = & (\mathbf{F}_{i1} [\mathbf{D}_{11} + \mathbf{V}_1 \mathbf{V}'_1] + \mathbf{F}_{i2} [\mathbf{D}_{21} + \mathbf{V}_2 \mathbf{V}'_1]) \mathbf{F}_{1j} \\ & + (\mathbf{F}_{i1} [\mathbf{D}_{12} + \mathbf{V}_1 \mathbf{V}'_2] + \mathbf{F}_{i2} [\mathbf{D}_{22} + \mathbf{V}_2 \mathbf{V}'_2]) \mathbf{F}_{2j}. \end{aligned} \quad (46)$$

The Schur complement of Σ is given by

$$\tilde{\Sigma} = \Sigma_{11} - \Sigma_{12} \Sigma_{22}^{-1} \Sigma_{21}.$$

Using the above formula as well as the fact that that \mathbf{F}_{12} , \mathbf{F}_{21} , \mathbf{D}_{12} , and \mathbf{D}_{21} are all zero matrices (since \mathbf{F} and \mathbf{D} are diagonal matrices and the submatrices along the diagonal are square), I can substitute equation 46 into the above formula to get

$$\begin{aligned} \tilde{\Sigma} &= \mathbf{F}_{11} [\mathbf{D}_{11} + \mathbf{V}_1 \mathbf{V}'_1] \mathbf{F}_{11} - (\mathbf{F}_{11} [\mathbf{V}_1 \mathbf{V}'_2] \mathbf{F}_{22}) (\mathbf{F}_{22} [\mathbf{D}_{22} + \mathbf{V}_2 \mathbf{V}'_2] \mathbf{F}_{22})^{-1} (\mathbf{F}_{22} [\mathbf{V}_2 \mathbf{V}'_1] \mathbf{F}_{11}) \\ &= \mathbf{F}_{11} \left(\mathbf{D}_{11} + \mathbf{V}_1 \mathbf{V}'_1 - \mathbf{V}_1 \mathbf{V}'_2 \mathbf{F}_{22} \mathbf{F}_{22}^{-1} [\mathbf{D}_{22} + \mathbf{V}_2 \mathbf{V}'_2]^{-1} \mathbf{F}_{22}^{-1} \mathbf{F}_{22} \mathbf{V}_2 \mathbf{V}'_1 \right) \mathbf{F}_{11} \\ &= \mathbf{F}_{11} \left(\mathbf{D}_{11} + \mathbf{V}_1 \left(\mathbf{I}_\ell - \mathbf{V}'_2 [\mathbf{D}_{22} + \mathbf{V}_2 \mathbf{V}'_2]^{-1} \mathbf{V}_2 \right) \mathbf{V}'_1 \right) \mathbf{F}_{11} \\ &= \tilde{\mathbf{F}} (\tilde{\mathbf{D}} + \tilde{\mathbf{V}} \tilde{\mathbf{V}}') \tilde{\mathbf{F}}, \end{aligned}$$

where $\tilde{\mathbf{F}} = (\text{diag}(\mathbf{D}_{11} + \mathbf{V}_1 \mathbf{G} \mathbf{V}'_1))^{1/2} \mathbf{F}_{11}$, $\tilde{\mathbf{V}} = \tilde{\mathbf{F}}^{-1} \mathbf{F}_{11} \mathbf{V}_1 \mathbf{G}^{1/2}$, and $\tilde{\mathbf{D}}$ has $\tilde{d}_i = 1 - \tilde{\mathbf{v}}_{i,\cdot} \tilde{\mathbf{v}}'_{i,\cdot}$ along the diagonal, where

$$\mathbf{G} = \mathbf{I}_\ell - \mathbf{V}'_2 [\mathbf{D}_{22} + \mathbf{V}_2 \mathbf{V}'_2]^{-1} \mathbf{V}_2.$$

Since $\tilde{\mathbf{F}}$ is a diagonal matrix, $\tilde{\mathbf{D}}$ has values $\tilde{d}_i = 1 - \tilde{\mathbf{v}}_{i,\cdot} \tilde{\mathbf{v}}'_{i,\cdot}$ along the diagonal, and $\tilde{\mathbf{V}}$ is $k \times \ell$, $\tilde{\Sigma}$ has a reduced rank of ℓ . \square

Corollary 3.1. *If a multivariate normal random variable \mathbf{X} is distributed $\mathcal{N}(\boldsymbol{\mu}, \Sigma)$, where Σ has a reduced rank of ℓ , then the covariance matrix of the conditional distribution also has a reduced rank of (at most) ℓ .*

Proof. Consider $\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \Sigma)$, where by assumption Σ has a reduced rank of ℓ . The distri-

⁵¹ \mathbf{V} will be partitioned into \mathbf{V}_1 and \mathbf{V}_2 , which both contain all ℓ columns of \mathbf{V} .

bution of $\mathbf{X}_1 | \mathbf{X}_2 = \mathbf{x}_2$ is a multivariate normal with mean $\tilde{\boldsymbol{\mu}} = \boldsymbol{\mu}_1 + \boldsymbol{\Sigma}_{12}\boldsymbol{\Sigma}_{22}^{-1}(\mathbf{x}_2 - \boldsymbol{\mu}_2)$ and covariance $\tilde{\boldsymbol{\Sigma}} = \boldsymbol{\Sigma}_{11} - \boldsymbol{\Sigma}_{12}\boldsymbol{\Sigma}_{22}^{-1}\boldsymbol{\Sigma}_{21}$. By proposition 3, $\tilde{\boldsymbol{\Sigma}}$ has a reduced rank of ℓ . \square

Proposition 4. *If for all s, t , $\Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G^e)) \geq \Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G'))$ for all $G' > G^e$, then $\bar{\eta}_{s,t}^e(G^e) \leq \bar{\eta}_{s,t}^e(G')$ for all $G' > G^e$ for $e \in \{R, E\}$.*

Proof. I begin by showing by that $V_{s,t}^{\text{out}}(e, \mathcal{G} \cup \mathcal{G}^e(G^e)) - V_{s,t}^{\text{in}}(e, \mathcal{G} \cup \mathcal{G}^e(G^e))$ is increasing in G^e for all e and \mathcal{G} . Denote this value as $V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G^e))$. Note that

$$V_{s,T}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G^e)) = -\frac{1}{1-\beta} (\Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G^e)) + \Upsilon_{c,s,t}(\{g_s\}, \kappa_T)),$$

where g_s is a generator of source s . Since $\Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G')) \leq \Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G))$ for all $G' > G$, it is therefore the case that in the final period of generator adjustments, T ,

$$V_{s,T}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G')) \geq V_{s,T}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G))$$

for all $G' > G$.

I next show that $V_{s,t+1}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G')) \geq V_{s,t+1}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G))$ for all $G' > G$ implies $V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G')) \geq V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G))$. Note that

$$V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G)) = \eta_{g,\text{out},t} - \eta_{g,\text{in},t} - \Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G)) - \Upsilon_{c,s,t}(\{g_s\}, \kappa_t) + \beta \mathbb{E} \left[V_{s,t+1}^{\text{diff}}(e, \mathcal{G}' \cup \mathcal{G}^e(G)) \right].$$

By our assumption and the fact that $\Pi_{c,s,t}$ is decreasing in G , the statement is true. By induction, it is therefore the case that

$$V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G')) \geq V_{s,t}^{\text{diff}}(e, \mathcal{G} \cup \mathcal{G}^e(G)) \quad \text{for all } G' > G. \quad (47)$$

The proposition follows from the above inequality. Note that by definition

$$\bar{\eta}_{s,t}^e(G) = -\Pi_{c,s,t}(e, \mathcal{G} \cup \mathcal{G}^e(G)) - \Upsilon_{c,s,t}(\{g_s\}, \kappa_t) + \beta \mathbb{E} \left[V_{s,t+1}^{\text{diff}}(e, \mathcal{G}' \cup \mathcal{G}^e(G)) \right].$$

Using the result given in equation 47 and the fact that $\Pi_{c,s,t}$ is decreasing in G , $\bar{\eta}_{s,t}^e(G^e) \leq \bar{\eta}_{s,t}^e(G')$ for all $G' > G^e$. \square

Table 14: Notation

Symbol	Description
t	indexes years (going from October 1 – September 30)
h	indexes wholesale intervals, which belong to a particular year t
f	indexes all firms (including competitive fringe)
N	number of strategic firms
c	indexes competitive fringe
\mathcal{G}_t	set of generators in year t
g	indexes generators
K_g	nameplate capacity of generator g (in MW)
$s(\cdot)$	returns the energy source of a generator
\mathcal{S}	the set of energy sources
\mathcal{Q}_t	distribution of demand in year t
\bar{Q}_h	perfectly inelastic demand shock in interval h
$\delta_{g,h}$	generator-specific capacity factor in interval h
$\bar{K}_{g,h}$	generator-, interval-specific effective capacity (in MW)
\underline{K}_g	minimum production level of generator g (in MW)
$q_{g,h}$	quantity generated by generator g in interval h (in kWh)
$c_{g,h}(\cdot)$	cost function for generator g in interval h
$\zeta_{1,g,h}$	linear cost parameter for generator g in interval h
$\zeta_{2,s}$	quadratic cost parameter for source s
τ_t	carbon tax in year t (in AUD / kg of CO ₂ -eq)
r_s	emissions rate (in kg of CO ₂ -eq / MWh)
$\mathbf{x}_{g,h}$	linear cost covariates for generator g in interval h
β_s	linear cost covariate parameters for source s
$\varepsilon_{g,h}$	idiosyncratic linear parameter cost shock for generator g in interval h
P_h	wholesale market price in interval h
$P_h(\cdot)$	inverse residual demand for strategic firms in interval h
$\pi_{f,h}(\cdot)$	wholesale profit function for firm f in interval h
M_s	yearly capacity maintenance cost for energy source s (in AUD / MW)
$\Pi_{f,t}(\cdot)$	yearly expected profit function for firm f in year t
\bar{P}_t	\bar{Q}_h -weighted average wholesale price in year t
$\mathcal{Q}_t(\cdot)$	returns the demand distribution in t as a function of \bar{P}_t
γ_g	fraction of capacity of generator g that is committed
κ_t	capacity price in year t (in AUD / MW)
$\psi_{f,h}(\cdot)$	penalty for firm f in interval h for failing to make available committed capacity (in AUD)
λ_s	source-specific refund penalty factor
$\Upsilon_{f,t}(\cdot)$	optimal net capacity payment for firm f in year t
Γ	set of possible combinations of generators
F	fixed adjustment cost
$C_{s,t}$	cost of new generator capacity of energy source s in year t (in AUD / MW)
$\eta_{f,\mathcal{G}}$	idiosyncratic generator adjustment cost for firm f and adjustment decision \mathcal{G}
β	discount rate (at yearly level)
$\sigma_{f,t}(\cdot)$	policy function for firm f in year t
T	final year in which possible to adjust set of generators