

Spillovers from ancillary services to wholesale energy markets

Jesse Buchsbaum*

Catherine Hausman**

Johanna L Mathieu***

and

Jing Peng***

In electricity markets, generators are rewarded for providing energy and for enabling grid reliability. The two functions are compensated separately: with energy market payments and ancillary services market payments. We provide evidence of changes in the generation mix in the energy market that are driven by exogenous changes in an ancillary services market. We provide a theoretical framework and quasi-experimental evidence for understanding the mechanism: it results from the multi-product nature of power plants combined with discontinuities in costs. Although much research focuses solely on the energy market, our results suggest that spillovers between the two markets are important.

1. Introduction

■ In electricity markets, generators are rewarded both for providing energy and for enabling grid reliability. The two functions are compensated separately – energy provision is compensated in the energy market, whereas grid reliability is compensated in the ancillary services market.¹

*Energy & Environmental Lab, University of Chicago, Chicago, IL, 60602, United States; jbuchbaum@uchicago.edu.

**Gerald R. Ford School of Public Policy, University of Michigan, Ann Arbor, United States; chausman@umich.edu.

***Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, United States; jl-math@umich.edu, jingpeng@umich.edu.

We are grateful to Jim Archsmith, Severin Borenstein, Karl Dunkle Werner, Ken Gillingham, Akshaya Jha, Jenya Kahn-Lang, Justin Kirkpatrick, Ömer Karaduman, Gordon Leslie, Matt Tarduno, Liz Wachs, and various conference and seminar attendees for helpful comments. This research was funded by the Alfred P. Sloan Foundation. The authors do not have any other financial relationships that relate to this research.

jbuchbaum@uchicago.edu

To date, the economics literature has largely focused on energy provision, even as other academic literatures, policymakers, and grid regulators have more carefully considered ancillary services. Ancillary service markets are interesting and important in their own right: they procure services that prevent brownouts and blackouts and ensure power quality. Moreover, changes in ancillary services markets can impact the behavior of generators in the much-larger energy market. Although these market interactions have been extensively studied by engineers using optimization models and simulations, quasi-experimental evidence is largely lacking. In this research, we show that exogenous policy changes implemented in the ancillary services portion of a large East Coast electricity market have changed the behavior of coal and natural gas generators in the energy market.

We begin with a stylized model to demonstrate how energy provision and ancillary services provision interact. Key features of the model include (i) power plants are multi-product suppliers; (ii) power plants tend to operate within a somewhat narrow operational range defined by non-zero minimum and maximum constraints; (iii) policy and market changes can cause power plants to operate at minimum load rather than being off. Importantly, the minimum load of many generators (a physical constraint) is non-negligible—although the related literature frequently ignores this constraint, it may be as high as 50% or more of capacity. To summarize, changes along the extensive margin—which units are turned on—can lead ancillary services markets to have outsized impacts on energy markets.

We next turn to empirical analysis of an ancillary services market: the frequency regulation market in PJM. PJM is the largest wholesale electricity market in the US, serving major population centers on the East Coast and dispatching nearly one fifth of all generation capacity in the lower 48 states. Frequency regulation refers to the short-timescale balancing of supply and demand by grid operators; we describe it in depth below. We leverage policy-induced quasi-experimental variation in the amount of frequency regulation required by grid operators. As a result, we identify how changes in the provision of frequency regulation by power plants impact the electricity market as a whole. We show that increases in the required frequency regulation capacity induce changes in the composition of power plants providing energy generation. For a 100 MW increase in the frequency regulation requirement, we estimate an additional 360 MWh from combined cycle plants over the course of one hour in the energy market and a corresponding decrease from boiler units.² These results are qualitatively similarly across a broad suite of robustness checks, with estimated increases of combined cycle units of around 300 to 460 MWh.

Because combined cycle plants primarily use natural gas whereas boiler units use coal, we also see a change in the fuel used to provide energy. Specifically, we find that increases in the regulation requirement lead to an increase in natural gas usage and a decrease in coal and oil. As a result, for every 100 MW of increased frequency regulation, CO₂ emissions fall by 240 metric tons per hour in our sample, with robustness checks showing a range of 200 to 370 tons. For the time period we study, the PJM market implemented several changes to *decrease* the regulation requirement. Although doing so can reduce the system-wide private cost of electricity provision, in this case it may have inadvertently led in the short term to higher CO₂ emissions. More generally, changes to ancillary services compensation are being considered as the electrical grid evolves in response to climate policy – as such, unintended CO₂ emissions changes in this context are particularly relevant.

¹ Throughout, we refer to the “energy market” and the “ancillary services market” following the language used in the electricity industry. We note, however, that one could instead think of this as a single electricity market for two related but distinct products: energy provision and grid reliability. Moreover some in the electricity industry consider energy provision a *product* and ancillary services a *service*. We use the term “multi-product” throughout in keeping with the usage of this term in economics.

² We use megawatts (MW) for capacity and megawatt-hours (MWh) for generation. A 1 MW unit operating at full capacity for one hour generates 1 MWh of electricity. The regulation requirement is a market-wide capacity requirement, measured in MWs. Electricity generation is sold as a function of energy provided over the course of some time frame, measured in MWhs.

At first glance, the magnitude of the generation mix change is surprising. However, the stylized model points toward potential mechanisms: changes along extensive margins, combined with minimum constraints. As such we next provide empirical evidence supporting this mechanism. We show that increasing the regulation requirement causes boilers to be dispatched at lower *levels* of generation in our sample (i.e., a change along the intensive margin). However, combined cycle plants are dispatched more *frequently* (i.e., a change along the extensive margin). These effects are consistent both with the overall generation impacts and with the stylized model.

These results make several contributions to the energy and environmental economics and the industrial organization literatures. First, we contribute to a still-small empirical literature in energy economics that analyzes electricity markets other than the energy market. One strand of the economics and engineering literature explores ancillary services markets with optimization models or simulation approaches (Hirst and Kirby, 1998; Just and Weber, 2008; Yu and Foggo, 2017). However, empirical analysis of ancillary services markets, particularly in how they interact with energy markets, is limited,³ despite there being a large empirical literature on wholesale electricity markets.⁴ We show that ignoring the ways that energy markets interact with these other markets can lead to incorrect conclusions about the impacts of policy changes.⁵

Second, we contribute to a strand of the electricity literature that emphasizes the importance of understanding how technical constraints impact power plant behavior, especially when considering generators as multi-product firms. Perhaps most closely related is Mansur (2008), which shows that ignoring intertemporal constraints gives an inflated estimate of the welfare impact that restructuring electricity markets had in the late 1990s. Most previous empirical research had focused on merit-order dispatch without considering intertemporal constraints such as minimum load, startup costs, and ramping. Also related are Wolak (2007); Reguant (2014), and Jha and Leslie (2021), which investigate the role of ramping costs and startup costs in generator behavior and market outcomes. Finally, Gowrisankaran et al. (2016) shows how the intermittency of renewables interacts with the need for reserve markets, ultimately impacting the system-wide costs of generation. We show that minimum load constraints can have a large impact on plant behavior, a point related to the role of technical constraints investigated in these other articles. We additionally show that the existence of multiple related markets can have significant impacts on plant behavior. We argue that power plants should be considered multi-product firms, and that limiting attention to just one of the markets might lead to incorrect or incomplete conclusions about plant behavior.

The behavior of multi-product firms has been the focus of a growing body of work in industrial organization and in international trade. Researchers have shown that examining how firms optimize *across* different products plays a key role in understanding productivity differences across firms; the behavior of firms with market power; and the impacts of trade policy, exchange rate movements, demand shocks, and more (Johnson and Myatt, 2006; Eckel and Neary, 2010; De Loecker, 2011; Chatterjee et al., 2013). Nonetheless, studies of the electricity market have tended to treat firms as providers of a single good – electricity generation – rather than multiproduct firms, with the exception of an older literature on the optimal regulation of natural monopolies that provide multiple goods (for instance, Mayo, 1984). Our ability to model the production of electricity with an engineering-based model makes clear how the degree of complementarity versus substitutability in production matters for outcomes in multi-product firms.

³ The primary exceptions are: Doraszelski et al. (2018), which estimates models of firm learning and convergence to equilibrium in a newly deregulated frequency response market in the UK; Knittel and Metaxoglou (2008), which examines ancillary services in the context of the California electricity crisis; and Schwenen (2015), which examines New York's capacity market. Jha and Wolak (forthcoming) examines the impact of "explicit virtual bidding" on the cost of electricity provision, focusing on fuel costs but also incorporating the costs of ancillary services provision.

⁴ See Borenstein et al. (2002); Fabrizio et al. (2007); Borenstein and Bushnell (2015); Cicala (2015); Davis and Hausman (2016); Holland et al. (2016a); Cullen and Mansur (2017); Leslie (2018); Hortaçsu et al. (2019), among many others.

⁵ Our results are also somewhat related to the literature on spillover effects within the energy market, for example, from solar to fossil power plants (Bushnell and Novan, 2021) and from hydro to fossil power plants (Archsmith, 2022).

Given the large number of industries with multi-product features (refining, airlines, freight transportation, manufacturing, to name a few), these mechanisms are of widespread relevance.

Third, this research contributes to policy discussions about several ongoing developments in electricity markets: changes in the way frequency regulation is procured and compensated, the introduction of utility-scale batteries, and the increasing deployment of renewable electricity (MIT Energy Initiative, 2011; Department of Energy, 2013, 2016; Hledik et al., 2017). Across the country, frequency regulation markets have seen multiple changes in recent years. In 2011, the Federal Energy Regulatory Commission (FERC) issued Order 755 (Federal Energy Regulatory Commission, 2011), which required grid operators to change their frequency regulation compensation mechanisms; we give details below. Various electricity markets across the US have responded with differing changes to their frequency regulation markets (Department of Energy, 2013; Tabari and Shaffer, 2020). These compensation mechanisms favor some resource types more than others, so supply in the regulation market (and therefore dispatch in the energy market) is likely to be affected. The extent to which these changes in compensation mechanisms have impacted electricity markets has not been thoroughly analyzed in the energy economics literature.

Moreover, there has been a growing interest in energy storage devices, such as utility-scale batteries, to provide frequency regulation and other grid support services. Within the PJM market we study, batteries have largely been deployed for frequency regulation, rather than for the intertemporal arbitrage⁶ potential explored in energy economics research (Carson and Novan, 2013; Holladay and LaRiviere, 2018; Antweiler, 2021; Kirkpatrick, 2018; Ambec and Crampes, 2019; Linn and Shih, 2019; Castro, 2020; Butters et al., 2021; Karaduman, 2021).⁷ Worldwide, a primary use of battery storage is for frequency regulation (International Renewable Energy Agency, 2017; Deloitte, 2018). The behavior of batteries providing ancillary services may differ tremendously from that of batteries providing arbitrage – both because of the way the relevant markets are designed and because of the timescale of use (e.g., seconds versus hours), and our results point toward the need for careful study of the effects of this kind of battery deployment.

Finally, the rise of intermittent renewables such as wind and solar generation can increase the amount of frequency regulation required in electricity markets (Kirby, 2004; MIT Energy Initiative, 2011).⁸ As generating technologies continue to evolve and batteries and renewable resources play a larger role in both markets, the interactions between energy and ancillary services markets are likely to continue to be important.

2. Background

Ancillary services and frequency regulation. Electricity markets are actually made up of numerous interrelated markets: energy, capacity, and several types of ancillary services markets.⁹ The energy market is the most studied and best understood by economists—this is where firms are compensated for generating electricity to be used by residential, commercial, and industrial customers. In ancillary service markets, generators are compensated for providing services that enable grid reliability – for example, frequency regulation and other types of reserves. Because the same generators are suppliers of both energy and ancillary services, the structure of ancillary service markets may have important spillovers in the energy provision market. Despite this, there

⁶ For batteries, arbitrage involves charging from the grid when the price is low and selling electricity to the grid when the price is high. As we discuss later, this is not the primary use of most grid-connected batteries in PJM.

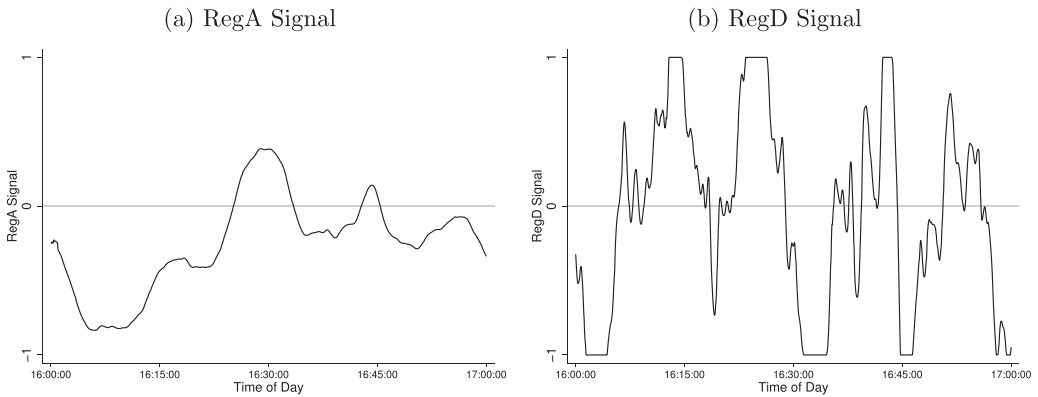
⁷ There is also a related literature on the use of hydroelectric facilities for storage, again focusing on storage for arbitrage purposes; see, for example, Liski and Vehviläinen (2020).

⁸ Ovaere and Gillingham (2019) examine the empirical impact of renewables on the cost of ancillary services provision.

⁹ By energy market, we refer to the sale of electricity, in MWh, in a wholesale market. In PJM, this is called simply the “energy market.” We sometimes refer to “energy provision” to distinguish from energy markets more generally such as oil markets. As the electricity economics literature frequently does not cover ancillary services markets, it frequently uses terms like “electricity market,” “power market,” and “wholesale market” without specifying whether the market is for providing energy or capacity or ancillary services or some combination.

FIGURE 1

EXAMPLE REGULATION SIGNALS.



Note: This figure shows the RegA and RegD signals in PJM from 4 pm to 5 pm on July 19, 2019. Data are from PJM.

has been very little empirical research into ancillary service markets. In this article, we focus on frequency regulation, motivated by ongoing policy changes in this market.

Electricity markets are unique in that demand must constantly equal supply, a responsibility that falls on grid operators. However, there are frequent fluctuations in demand and supply, creating small mismatches between the two. When supply exceeds demand, frequency (the number of cycles per second of the alternating current) rises above the nominal frequency (i.e., 60 Hz in North America); when demand exceeds supply, frequency falls below the nominal frequency. If the grid frequency departs enough from the nominal level, it can cause damaged equipment or brownouts and blackouts for customers (Federal Energy Regulatory Commission, 2011).

To prevent this from happening, system operators have created markets to regulate the frequency of the grid, a service called “frequency regulation,” “regulation reserves,” “load frequency control,” “secondary frequency control,” or simply “regulation.”¹⁰ In the typical market, the system operator sets a frequency regulation requirement—this is the total capacity (in MW) that must be set aside for provision of frequency regulation. It is sometimes time-invariant, sometimes a function of forecasted demand, or possibly also a function of renewables forecasts. Generators can then bid a portion of their capacity to be available to grid operators to either increase or decrease generation (relative to their set point) at any time (within the frequency regulation contract duration), depending on the needs of the grid. The independent system operator¹¹ sends out a signal (automatic generation control, or AGC) to participating units, to which they automatically make small adjustments in their generation to balance supply and demand.¹² Typically, these small adjustments are made within seconds (Zhou et al., 2016). An example signal is shown in Figure 1.

Some system operators use separate signals for “regulation up” versus “regulation down.” The PJM market that we study does not use separate signals for up and down movements. For the time period we analyze, this signal is energy-neutral within a short time-frame (15 minutes), so that units always return to their initial set point (Monitoring Analytics, 2018).

¹⁰ Background on frequency regulation and other ancillary services is provided in Hirst and Kirby (1997); Kirby (2004); Hummon et al. (2013); Tacka (2016); Zhou et al. (2016).

¹¹ An independent system operator is a non-profit entity that operates the wholesale electricity market.

¹² FERC Order 755 defines frequency regulation as “the capability to inject or withdraw real power by resources capable of responding appropriately to a system operator’s automatic generation control signal in order to correct for actual or expected Area Control Error needs” (Federal Energy Regulatory Commission, 2011).

To participate in the market, a power plant must have the technical capability to follow the operator's regulation signal. It must also be dispatched at a non-zero level of generation, with headroom and footroom to follow the signal. That is, it cannot be operating at its minimum or maximum constraints because it must be able to move up and down in response to the operator's signal (Kirby, 2004). The resource mix contributing to frequency regulation varies across regions. In PJM, it is a mix of coal, natural gas, hydro, and battery storage (Monitoring Analytics, 2018).

Generators take several cost considerations into account when deciding whether and how to bid in a regulation market. Small fluctuations around the generator's set point impact the plant's heat rate, thus changing fuel costs. Providing regulation also imposes wear and tear on the plant (Hirst and Kirby, 1997; Hummon et al., 2013) and can change SO₂ and NO_x emissions, which in some markets are priced.¹³

Over time, system operators have moved toward rewarding regulation providers for both the *capacity* committed to regulation and the *quality* of regulation services provided.¹⁴ Specifically, some units, such as coal-fired boilers, have significant physical inertia that prevents them from responding quickly to regulation signals. In contrast, units such as batteries, hydro generators, and some natural gas generators are able to respond very quickly to the signal, which gives the system operator greater flexibility and speed in restoring the system-wide frequency to its desired level. To incorporate this difference across suppliers, PJM uses a more complicated set of payments.¹⁵ First, PJM sends out two separate regulation signals, one termed "RegA" (for slower-responding units) and one termed "RegD" (for faster-responding units). Moreover, units receive payments both for their capability (i.e., the quantity of MWs offered) and for their performance (the accuracy with which the unit responds to the operator's signal). In Section 3, we discuss how the compensation of both capability and performance might impact our results. We discuss the entry of utility-scale batteries for frequency regulation in Section 7.

Related literature. One strand of the economics and engineering literature explores ancillary services markets with optimization models and simulations (Hirst and Kirby, 1998; Just and Weber, 2008; Yu and Foggo, 2017). In particular, Hirst and Kirby (1997) notes that the minimum and maximum constraints of individual generators, when combined with the need to provide headroom and footroom for regulation provision, can lead to a dispatch of units across the system that would not appear least-cost if one only considered the marginal cost of energy provision, and it can also lead to significant complexity in which units are dispatched. Simulations showing changes in dispatch to meet regulation requirements are also given in Hummon et al. (2013). This informs our stylized model in Section 3.

A small number of *ex-post* empirical articles examine how additional operational constraints can lead to out of merit dispatch; for example, Mansur (2008), Reguant (2014). These articles focus on dynamic constraints related to startup costs and ramping. However, empirical analysis of ancillary services markets, particularly in terms of how they interact with energy markets, is limited, despite there being a large literature on wholesale electricity markets.

Several articles use optimization models and/or small-scale simulations to show how frequency regulation markets and other ancillary services markets interact with energy markets. Notably, one report (Atanacio et al., 2012) simulates the impact of storage providing regulation in the PJM system.¹⁶ Specifically, it looks at the emissions changes expected to result across the

¹³ The exact cost associated with additional wear and tear is not generally known for individual generators; simulations typically assume a cost that varies across fuel types (see, e.g., Hummon et al. (2013)).

¹⁴ This has been spurred by FERC Order 755 (FERC 2011), which requires that independent system operators change their frequency regulation compensation mechanisms to "pay for performance" systems that recognize the differential speed and accuracy with which different resources respond to the regulation signal. Each independent system operator has designed its pay for performance compensation mechanisms differently (Department of Energy, 2013; Tabari and Shaffer, 2020).

¹⁵ This payment mechanism in PJM was established in October 2012, following FERC Order 755.

¹⁶ Research from the empirical economics literature exploring other aspects of the PJM market includes Mansur (2008); Mansur and White (2012); Abito et al. (2022).

PJM system when fast-acting storage devices provide 10%, 25%, or 50% of frequency regulation services. It is not clear if the study's proprietary simulation model includes the unit commitment and/or economic dispatch algorithms used by PJM. So, it is not clear if storage providing frequency regulation can impact commitment in the model, nor how exactly it impacts dispatch. The simulation results show small emissions reductions from storage entry, because conventional plants operate less efficiently when providing regulation services. However, the report noted that the interaction between the energy market and the frequency regulation market are complicated and could limit the emissions benefits of storage, and the study's analysis of California's system showed the potential for increased CO₂ emissions (Atanacio et al., 2012).

Two additional articles that examine emissions impacts of using storage for frequency regulation are Lin et al. (2016) and Ryan et al. (2018). Ryan et al. (2018) uses a small test system to show that changes in the frequency regulation market can lead to changes in the fuel mix and therefore emissions changes. Indeed, the authors find that “[c]hanges in generator commitment and dispatch caused by the addition of energy storage were the most significant contributors to the energy storage system's environmental impact” (p 10172). Hummon et al. (2013) also explores the interaction between reserve markets and energy markets using a simulation approach, although the research does not examine emissions outcomes. Cho and Kleit (2015) explores the optimal bidding strategy for a storage device that can provide ancillary services. Finally, in Yu and Foggo (2017), “[s]imulation results with a realistic battery storage system reveal that the majority of the market revenues comes from frequency regulation services” (p 177).

Although several of these articles examine ancillary service markets, and even consider spillovers into the energy provision market, this article is the first to our knowledge to show quasi-experimental evidence of these spillover effects, which lead to fuel use changes and therefore changes in emissions.

3. Stylized model of the electricity market

The system operator's optimization problem. In this section, we develop a stylized model of the regulation and energy markets, following Kirschen and Strbac (2004). The goal is not to fully represent all the complexities of the electrical grid, but to show some of the mechanisms by which an increase in the regulation requirement will change generation decisions in the energy market. Specifically, we elucidate how a system operator optimally procures energy and regulation services, especially in the presence of constraints over minimum generation. We use a stylized version of the system operator's problem, which is essentially a single-period unit commitment problem.¹⁷ Although we focus on regulation provision, the model has features that apply to reserves markets in general.

We assume that there are multiple heterogeneous thermoelectric generating units participating in an energy market and a regulation market. We evaluate how the plants operate before and after the regulation requirement increases. We use the following notation:

- x_i - generation for energy market for unit i ¹⁸
- y_i - one-sided capacity committed to the regulation market for unit i ¹⁹
- p_x - energy market price per MWh
- p_y - regulation market price per MW

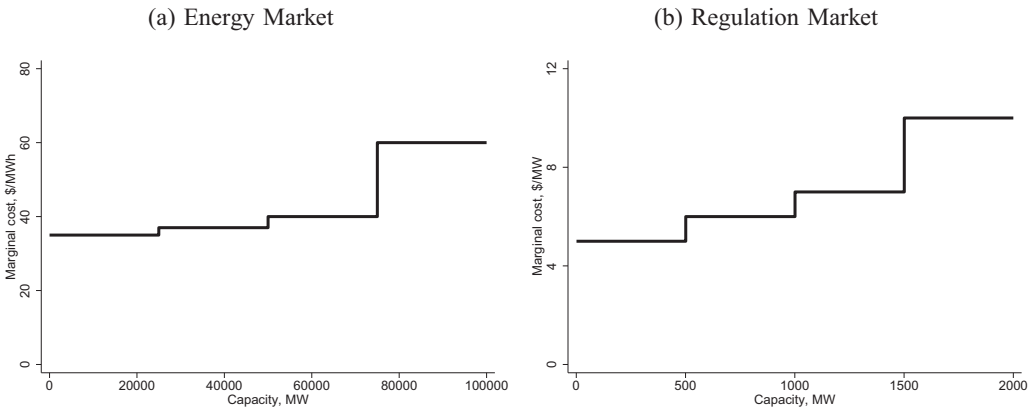
¹⁷ Note we do not model the bidding behavior of individual plants. We are essentially assuming that there is no market power, and so plants bid their marginal costs. This is realistic if there are many firms and/or if regulators are able to observe marginal cost and thus punish anti-competitive bidding. The latter is especially likely to be true in our context. Annual market monitoring reports state that the exercise of market power has not generally been observed in PJM's frequency regulation and energy markets (for instance, https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2-sec1.pdf, and other years' reports).

¹⁸ This is the set point around which regulation will be provided, if the generator offers frequency regulation.

¹⁹ By one-sided, we mean the capacity available in either direction. The generator must be available to deviate up or down from its set point x_i by the amount y_i .

FIGURE 2

SHORT-RUN MARGINAL COST CURVES



Note: These figures show stylized marginal cost curves for a hypothetical energy market and regulation market, with four types of participating generating units.

- m_i - marginal cost of generation for unit i , a function of fuel use and wear and tear
- n_i - marginal cost of regulation for unit i , a function of wear and tear
- M_i - minimum generation for unit i , a physical constraint
- C_i - maximum generation for unit i , a physical constraint
- r_i - maximum regulation for unit i , a physical constraint²⁰

Additionally, we make the following assumptions:

- Firms are sufficiently small that their actions do not influence the market price in either the regulation or the energy market (i.e., no market power).
- Constant marginal costs of generation and of regulation for each unit, with no fixed costs. These are heterogeneous across plants, a function of the technology installed (fuel choice, prime mover type, etc).²¹
- $r_i < C_i - M_i$ for each unit i .²²

Focusing on the energy market and leaving aside (for now) minimum constraints, this yields a short-run marginal cost curve that is a step function, as shown in the left-hand panel of Figure 2. The height of each step is the marginal cost m_i for each fuel and technology combination, and the width is the maximum generation C_i for each fuel and technology combination. Typically natural gas combined cycle units and coal-fired units are the cheapest to operate, and natural gas combustion turbines operate at much higher cost and with smaller capacities.

Many articles in the economics literature focus on the energy market and elide minimum constraints, yielding a supply curve much like the left-hand panel in Figure 2 (Borenstein et al., 2002; Davis and Hausman, 2016). Dispatch order would then follow a least-cost framework, in which the lowest cost units are dispatched, up until demand (exogenously determined) has been fulfilled. In such a supply curve, when demand exogenously changes, one can examine whether a

²⁰ A typical power plant can commit at most 10–20% of its capacity to regulation (Makarov et al., 2008; Atanacio et al., 2012).

²¹ A fully realistic model of the electric grid would allow for non-linear costs within each unit, as in Hirst and Kirby (1997). However, constant marginal costs are frequently assumed in the electricity economics literature (Borenstein et al., 2002; Mansur, 2008; Davis and Hausman, 2016) and are sufficient to illustrate the mechanisms at play in our model.

²² This is reasonable to assume in our empirical setting. As noted above, a power plant can typically commit 10–20% of capacity to regulation. Typical minimum constraints are around 30–50% of maximum capacity. For further discussion of this constraint, see Kirschen and Strbac (2004).

different unit is on the margin to examine price impacts as well as emissions impacts. This kind of framework is also used in the literature to examine what happens when fuel price changes lead to a re-ordering of the dispatch, that is, a change in which units are least-cost.

Focusing on the regulation market, our framework implies a similar short-run marginal cost curve, again a step function (right-hand panel of Figure 2). Here the height of each step is the marginal cost n_i for each fuel and technology combination, and the width is the maximum regulation r_i for each fuel and technology combination.

Solving for the competitive equilibrium in the energy market when there is no regulation market and there are no minimum constraints is simple, as described above. However, when the system operator is minimizing the cost across these two markets and when minimum constraints are incorporated, we have a more complicated mixed integer linear programming problem:

$$\begin{aligned} \min_{x_i, y_i} \left(\sum_{i \in \{1, 2, \dots, I\}} m_i x_i + n_i y_i \right) \quad & \text{s.t.} \quad \sum x_i = \text{demand}; \\ & \sum y_i = \text{regulation requirement}; \\ & x_i + y_i \leq C_i \quad \forall i; \\ & x_i - y_i \geq M_i \quad \text{or} \quad x_i = y_i = 0 \quad \forall i; \\ & 0 \leq y_i \leq r_i \quad \forall i; \end{aligned} \quad (1)$$

The operator minimizes the total cost of generation and regulation provision, subject to a number of constraints. The total demand and regulation requirements must be satisfied.²³ Units cannot commit more than their total capacity across the two different markets; they must have sufficient headroom if they offer regulation. The system operator can choose not to dispatch any particular unit, but if the unit operates, it must be at least at its minimum constraint. As a result, if it commits non-zero capacity to the regulation market, it must be at its minimum constraint *plus* its regulation provision in the energy market, that is, $x_i - y_i \geq M_i$ (i.e., have footroom). These minimum constraints are frequently elided in empirical research, but they are nontrivial. The typical unit in our data has a minimum constraint of 30–50% of its maximum capacity.²⁴ The constraint is related to technical restrictions – operating a plant below minimum load can damage plant equipment.²⁵

In this model, corner solutions are possible for many individual generating units. For instance, a unit might operate at maximum capacity in the energy market ($x_i = C_i$) and not participate in the regulation market ($y_i = 0$). It might instead operate just below maximum capacity to fully participate in the regulation market, that is, with $x_i = C_i - r_i$ and with $y_i = r_i$. It might similarly operate just above minimum capacity to fully participate in the regulation market, with $x_i = M_i + r_i$ and with $y_i = r_i$. There may also be marginal units with generation levels between minimum and maximum capacity, and/or with regulation commitments between 0 and r_i .

Now suppose that the regulation requirement is exogenously increased, and that the change is large enough that the marginal unit cannot provide the additional regulation. The system operator will procure regulation from an additional unit. Suppose this does not require a change in which plants are dispatched in the energy market (an unrealistic assumption to which we return momentarily). Then the system operator might change the energy and regulation procurement from an individual generating unit in multiple ways, as shown in Table 1.

²³ The magnitude of the regulation requirement refers to the one-directional capacity needed across all units.

²⁴ The median PJM combustion turbine in our data has a minimum constraint at 50% of its maximum; the median non-CT in our PJM data has a minimum constraint at 30% of its maximum capacity.

²⁵ Minimum load constraints are sometimes determined by environmental compliance, if emissions rates are very high at low levels of generation. Cost considerations can also be a factor, if fuel efficiency is very low at low levels of generation.

TABLE 1 Some Potential Effects of an Increase in the Regulation Requirement

Pre-period x_i	Post-period x_i	Change in x_i	Pre-period y_i	Post-period y_i	Change in y_i
$x_i = C_i$	$x_i = C_i - r_i$	$-r_i$	$y_i = 0$	$y_i = r_i$	r_i
$x_i = 0$	$x_i = M_i + r_i$	$M_i + r_i$	$y_i = 0$	$y_i = r_i$	r_i

Note: This table shows two potential effects of an increase in the regulation requirement on a generating unit participating in the energy market. In the first row, the generating unit backs down from maximum capacity C to have enough headroom to provide regulation. In contrast, in the second row, the generating unit enters the energy market to have enough footroom to offer regulation. In both cases, the generating unit increases its regulation provision (from zero to r). However the cases show effects in opposite directions and of differing magnitudes in the energy market. Other outcomes are possible as well – for instance if the generating unit had previously been offering some quantity between zero and C in the energy market, or because of market-wide re-dispatch in the energy market.

To be able to provide regulation services, it is possible that a unit that had previously been operating at maximum capacity C_i would need to back down from its maximum capacity. This could occur if the regulation price change is large enough to outweigh the lost revenues from participating less in the energy market. This outcome is demonstrated in the first row of Table 1. It is also possible, however, that a unit that had not been participating in either market could be induced to enter *both* markets. In this scenario, a unit would move from zero generation in the energy market to at least a bit above its minimum operational constraint, operating at $M_i + r_i$ (or more) to be able to sell r_i regulation services. This could occur if its marginal energy cost m_i is above the market clearing energy price p_x , but the additional revenues in the regulation market make up for losses in the energy market. This outcome is demonstrated in the second row of Table 1. In short, an increase in the regulation requirement could lead an individual unit to either increase or decrease the energy it sells in the energy market. Moreover, it is possible for the change in the energy market to be *larger* than the change in the regulation market, if a unit is induced to move from not generating at all to generating above its minimum constraint.

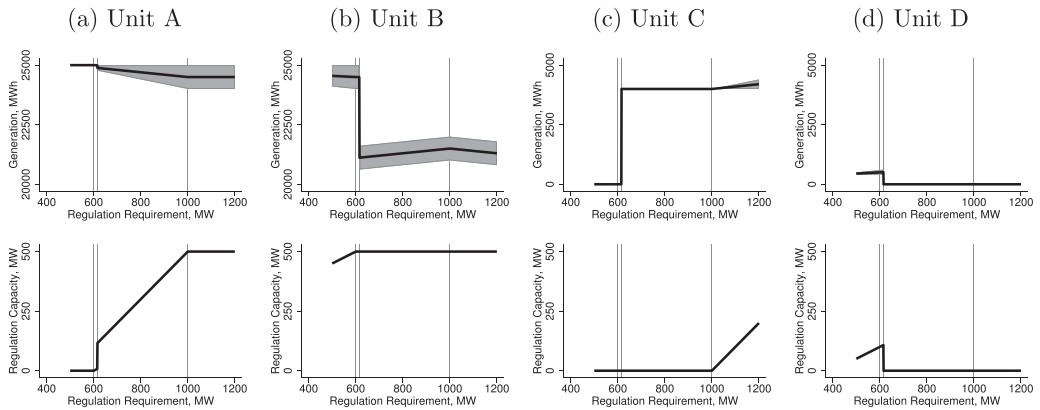
We must also consider the follow-on changes for *other* units in the energy market. As energy demand is exogenous and inelastic, any changes induced by one unit, as described in Table 1, must be offset by an equal amount across all other units (neglecting changes in losses due to changes in power flows, which we have not modeled). That is, the change in the regulation requirement could induce not only changes in p_y , but also changes in p_x and therefore a different set of plants committed, and different dispatch levels for those plants, in both the regulation and energy markets. The system as a whole could move to a different equilibrium with different inframarginal units, and with some units changing by more than the regulation requirement change. How the system changes will depend on the ways short-run operating profits in one market (e.g., $p_x - m_i$) compare to short-run operating profits in the other market (e.g., $p_y - n_i$) across the entire set of generators.

Simulated market. We construct a four-unit model, showing that a regulation requirement change can have a wide range of impacts in the energy market. We then solve for the equilibrium, exogenously changing the regulation requirement to show how changes occur along the extensive margin for various plants. The four units represent three baseload units, with differing marginal costs of energy and regulation, and one peaker unit with higher marginal cost for both services (details in Online Appendix). All four units have minimum operational constraints.²⁶ All four units are capable of following the regulation signal, which is an energy-neutral signal (units return to their initial set point within a specified time frame). The four units combined must meet an exogenous perfectly inelastic demand requirement as well as a perfectly inelastic regulation requirement.

²⁶ The minimum is the same for the three low-cost plants. The high-cost unit has a smaller minimum operational constraint, representing the fact that the peaking portion of the electricity market is made up of many small peaker units that can each be dispatched at quite small levels of generation.

FIGURE 3

SIMULATED FOUR-UNIT MODEL



Note: This figure displays the equilibrium results for a four-unit model with energy and regulation output. The top row shows generation outcomes with a black line, surrounded by the regulation band in grey. Generation is in MWh provided (over one hour). The bottom row shows the capacity committed to regulation. Units are ordered left to right from least to most expensive, with the ranking the same across the generation and regulation markets (Unit A has the lowest marginal cost for both services; Unit D the highest). All four units face minimum and maximum constraints. Energy demand is held constant, and the regulation requirement varies exogenously across the x-axis. Discontinuities and kinks are shown with vertical grey lines, at a regulation requirement of 600, 615, and 1000 MW. Quantities are given in table form, along with cost and constraint details, in Online Appendix Table A1.

Figure 3 shows how each unit changes its generation (top row) and regulation provision (bottom row) as the regulation requirement is scaled up (results are also shown in table form in the Online Appendix, Table A1). In the top row, note the axes are scaled differently across units.

If there were no minimum constraints and no regulation requirement, Units A and B would provide energy at their maximum (25,000 MWh each) as they have the lowest marginal costs of energy provision. However, the minimum constraints and the regulation requirements change the equilibrium in qualitatively important ways.

Consider first the setting where the regulation requirement is set at 500 MW. Unit A produces the maximum possible energy (25,000 MWh), but Unit B provides only 24,550. It then uses its remaining capacity (450 MW) to provide regulation. Unit C is not dispatched to fill in the remaining 450 MWh to satisfy energy demand. Instead, the most expensive unit, Unit D, provides 450 MWh of energy and 50 MW of regulation services. This is because Unit D, a peaker, has a lower minimum generation requirement than does Unit C – in fact, it operates just at its minimum generation requirement. This illustrates how the minimum generation constraints can alter the dispatch order. (We caution that the results are particularly “lumpy” in that the minimum generation has an especially pronounced impact because there are only four generators; results would be less lumpy in a large market.)

Next, consider what happens as the regulation requirement increases from 500 to 550 or 600 MW. Unit B decreases its energy a bit, to be able to provide additional regulation – it must decrease energy provision to do so, because it had been operating at its maximum constraint when combining both energy and regulation. Unit D also provides a bit more regulation, but to do so, it must *increase* its generation, to maintain status above its minimum constraint. This illustrates how a unit wishing to provide additional regulation could conceivably increase *or* decrease its energy provision, depending on which (if any) of its constraints are binding.

Once the regulation requirement is increased to 601 MW, Unit A begins to decrease its energy, to be able to provide regulation. This is because Unit B is providing as much regulation as possible (500 MW) and cannot provide additional regulation. As the regulation

requirement continues to increase, up to 615 MW, additional 1-unit changes in the regulation requirement lead to Unit A decreasing its energy provision and increasing its regulation provision.

The most interesting change occurs when the regulation requirement increases to 616 MW. At this point, the least-cost solution involves dispatching Unit C at its minimum generation. Thus Unit D exits both markets. Previously, this had not been least-cost because of Unit C's minimum constraint. However, it is now least-cost for Unit C to operate at its minimum constraint, rather than to be turned off. So a change in the regulation requirement from 615 MW to 616 MW leads to a very different equilibrium across all units. Unit A decreases its energy provision by around 100 MWh and increases its regulation provision by around 100 MW. Unit B decreases its energy provision by around 3000 MWh and maintains the same amount of regulation provision. Unit C increases from 0 to 4000 MWh of energy, but does not provide any regulation. Unit D drops from over 500 MWh to 0 MWh of energy, and also exits the regulation market. This illustrates how a small change in the regulation requirement can lead to oversized changes in the energy market if it changes whether a unit switches between zero generation and operating at its minimum constraints.

Finally, the last change to occur in this figure is when the regulation requirement goes from 1000 to 1001 MW. Unit C provides the marginal regulation. To do so, it must increase its energy provision because it had been operating at its minimum constraint. Recalling that total generation is fixed, we see that Unit B decreases its energy provision as a result.

We make several caveats regarding the generalizability of our model. We have deliberately presented a stylized version of the energy and regulation markets, to show some of the ways that minimum constraints combine with the multi-product nature of power plants. In practice, there are two different regulation prices in the PJM market: units are rewarded separately for the quantity of MWs offered and for the accuracy with which they respond to the regulation signal. This will impact the mix of, for instance, natural gas combined cycle units versus coal units in the regulation market, because they have differing levels of accuracy. The mix of coal versus natural gas units in the regulation market will also be impacted by secular changes in fuel prices and thus the generation mix of the broader electrical grid.

Also, we have not modeled other features of the market that could interact with the minimum constraints. For instance, our model is static, and dynamic constraints such as minimum up and down times could matter. How exactly they would interact with frequency regulation provision would depend on demand profiles across the day, among other things. Moreover, in reality, system operators run multiple optimization algorithms because there are markets on different timescales: the system operator must make decisions at the day-ahead, hour-ahead, and real-time levels. How regulation interacts with unit commitment will be determined by what algorithms the system operator uses across these different timescales. Also, transmission congestion can matter; as Ryan et al. (2018) write, "we cannot make generalizations about the effects of congestion because, in practice, results would be strongly dependent on grid topology and parameters, generator sizing and location, and so on" (p 10172). Finally, our model consists of only four units; in practice electricity markets are of course much larger. More generating units will mean that supply is less "lumpy" and so one might expect less discontinuous changes than what is observed in Figure 3; however, in a real-world market, transmission congestion could shrink the number of units that are able to respond.

Overall, there are four primary takeaways from this stylized model: (i) there are potential nonlinearities in the impacts of a regulation requirement change; (ii) high marginal cost units can be dispatched over cheaper units because of minimum constraints; (iii) an increase in the regulation requirement can either increase or decrease generation at a given unit; and (iv) changes in generation at an individual unit can be bigger than the change in the regulation requirement. Thus we see that minimum constraints can be quite important here in that they create lumpiness in how the market responds to exogenous changes, although the economics literature tends to elide them for simplicity. Moreover, the two output markets can interact in

surprising ways, with outsized impacts of the regulation market on the energy market. Finally, the specific changes that will be observed following a regulation market change will depend on a suite of parameters. To understand how frequency regulation provision has spillover effects on energy provision, we next turn to an empirical exercise for a large electricity market in the U.S.

4. Data

■ We collect data from the Environmental Protection Agency's Continuous Emissions Monitoring System (CEMS) on hourly generation (MWh) and CO₂ emissions (metric tons)²⁷ at the generator level, for fossil-fuel-fired units.²⁸ From CEMS, we also observe the primary fuel source used by a generator each year (coal, natural gas, or oil) and the technology type of the generator (boiler, combined cycle, or combustion turbine). From EIA-860 data, we observe whether units are located in PJM. We also observe in EIA-860 whether units are operated by electric utilities, independent power producers, or as part of a commercial or industrial operation. We drop all commercial and industrial units, as they are unlikely to sell into the electricity market. We report our primary results for four technology categories of PJM units: boilers, combined cycle (CC) units, combustion turbine (CT) units, and all other PJM CEMS units aggregated. We also report results across four fuel types: coal, natural gas, oil, and others aggregated.²⁹

The CEMS data do not provide information on non-fossil units (e.g., nuclear, hydro, wind, municipal solid waste), nor does CEMS cover fossil-fuel fired units with capacity less than 25 MW. (For context, units smaller than 25 MW are quite small; the average capacity in EIA-860 data is over 350 MW for steam units in PJM.) To observe the behavior of these units, we calculate a residual category of generation (in MWh), equal to the difference between total demand reported by PJM and total generation reported in CEMS. This residual variable thus covers PJM units not in CEMS as well as net imports into PJM from other regions.

Ideally, we would also observe individual participation in the regulation market. However, this is considered sensitive market information and is not published by PJM. Instead, we can use the CEMS data to observe how generation behavior in the energy market changes as a function of the regulation requirement, which we do observe. Specifically, we collect hourly data, from PJM, on regulation market activity. Our primary explanatory variable is the hourly regulation requirement, in MW. The regulation requirement refers to a pre-determined quantity of regulation capacity that the independent system operator announces it will purchase. As we describe below, this amount varies over time because of several policy changes. In some periods, the regulation requirement is tied directly to the forecasted peak and valley demand for each day, so we also assemble data on these forecasts from PJM.

We also collect auxiliary data from a number of other source including PJM (total electricity demand), the Energy Information Administration (fuel prices), and NOAA (weather); further details are in the Online Appendix. Summary statistics are provided in Online Appendix Tables A2, A3, and A5. A time-series of generation by fuel types and technology types is provided in Online Appendix Figure A2. The sample is characterized by a reliance on coal generation and on natural gas generation. The mix of coal versus gas is fairly constant over the time period we study. Other fuel types are present (oil-fired generations, etc.), but are a very small portion of the energy market.

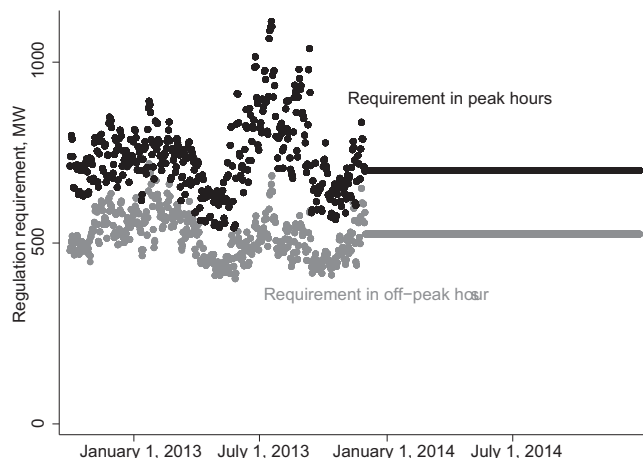
²⁷ The CEMS-reported CO₂ emissions are missing for approximately 9% of observations with non-zero heat input data, representing 2% of generation. In place of these missing values, we assume an emissions rate (per mmBtu of fuel used) equal to the median rate at the unit; see Online Appendix for details.

²⁸ CEMS reports *gross* generation rather than *net*, that is, not accounting for the generation used by the plant itself (or instance, to run pollution control equipment). Net generation is the variable of interest, because that is what is sold in the electricity market. Following Cicala (2022), we scale each unit's generation down from gross to net using monthly generation data from the Energy Information Administration's (EIA) form 923 dataset. This approach also resolves incomplete reporting for some combined cycle units. See Online Appendix for details.

²⁹ For details on "others aggregated," see Online Appendix.

FIGURE 4

REGULATION REQUIREMENT IN PJM



Note: The regulation requirement changes across hours within a day, hence the two different levels plotted on each day. Peak hours are defined 4 a.m. to midnight, and off-peak hours as midnight to 4 a.m. In the raw data, one hour (on 4/2/2013) is listed as having a regulation requirement of zero; this hour is dropped from the regressions. Data source is PJM.

5. Empirical evidence on generation and emissions

Identifying variation. We are interested in how exogenous changes in the frequency regulation market spill over into the behavior of generators in the energy market. As such, we leverage policy changes in PJM's regulation market over the period October 1, 2012 to December 31, 2014. We leverage quasi-experimental variation in the total regulation requirement set by the independent system operator, which changes several times. The benefit of focusing on this period is twofold: battery capacity for frequency regulation is limited and conventional generator entry and exit is small. This allows us to focus on the total regulation requirement and its impact on conventional generators.

As of October 1, 2012, the regulation requirement for peak hours was set at 0.78% of forecasted peak load; for off-peak hours it was set at 0.78% of forecasted valley load. On November 22, 2012, this ratio was reduced to 0.74%, then to 0.70% on December 18, 2012. More important than these minor changes is the change on December 1, 2013: the regulation requirement was changed from a percentage of the forecasted peak and valley load to a requirement of 700 MW of effective regulation during peak hours and 525 effective MW during off-peak hours.³⁰ This variation in the regulation requirement can be seen in Figure 4. Also apparent in Figure 4 is the considerable variation in the regulation requirement over this time period, from less than 500 to around 1000 MW, which provides us with substantial identifying variation.

A PJM report from 2011 describes the motivation behind these changes: “[d]ecreasing regulation requirements reduces regulation payments” and “[f]ewer resources providing regulation means more resources available for the energy market.”³¹

³⁰ Sources: http://www.monitoringanalytics.com/reports/pjm_state_of_the_market/2013/2013-som-pjm-volume2.pdf and <https://www.pjm.com/~media/documents/manuals/m12.ashx>. “Effective” regulation is a measurement that takes into account the performance of the units providing regulation and the substitutability across RegA and RegD units; see <https://pjm.com/~media/documents/manuals/m11.ashx>.

³¹ <https://www.pjm.com/~media/committees-groups/committees/mrc/20110915/20110915-item-13-rpstf-update-presentation.ashx>

In Section 2, we discuss how the regulation *signal* at any point in time is a function of mismatch between supply and demand – thus the signal itself is endogenous to market activity. However, the regulation *requirement* is a pre-determined capacity procurement – set in advance by policy – and thus is not endogenous to day-to-day or hour-to-hour market activity.

Although exogenously determined, the requirement could still be correlated with other determinants of generator behavior. For instance, the peak and valley forecasted load may impact generator behavior directly, in addition to being determinants of the regulation requirement – necessitating the inclusion of some controls in our regression.

Our regression takes the form:

$$G_{i,t} = \alpha_i + \beta_i R_t + X_i \Theta_i + \varepsilon_{i,t}, \quad (2)$$

where $G_{i,t}$ is generation at unit type i in hour t , R is the regulation requirement, and X_i is a vector of controls. Note this is estimated as a single time-series, but we index G with unit type i , because we can separately estimate the regression for multiple unit types, allowing the parameters to vary by unit type.³² Standard errors are clustered by sample week.³³

In this regression, we must control for forecasted peak and valley load,³⁴ as they directly determine the regulation requirement in the first part of the sample and may also directly impact generator behavior (i.e., not including these controls X_i would mean that $\varepsilon_{i,t}$ would be correlated with R_t).³⁵ The policy change thus allows us to separately identify the impact of forecasted peak and valley load from the impact of the regulation requirement. Specifically, variation in forecasted peak and valley loads during the second half of the sample identifies the effect Θ of these variables on generator behavior. Assuming that Θ does not change between the first and second halves of the sample, the first time period can then be used to estimate the impact of the regulation requirement on generator behavior conditional on the peak and valley forecasts (i.e., we can assume that $\varepsilon_{i,t}|X_i$ is uncorrelated with R_t). In the Online Appendix, we provide a simulation of this identification strategy, where we directly control the data-generating process.

One might also worry that other variables are correlated with both the regulation requirement and with generator behavior. Following the literature on generator behavior (Holland and Mansur, 2008; Wolak, 2011; Cullen, 2013; Cullen and Mansur, 2017; Fell and Kaffine, 2018; Leslie, 2018; Bushnell and Novan, 2021), we include additional control variables. We control for total demand in the PJM system; for fuel prices; and for weather.³⁶ Failing to include these could introduce bias if they are correlated with the regulation requirement.

We also follow the literature in including time period dummies (month of sample, hour of day, and day of week dummies) to control flexibly for other exogenous changes in the PJM market over this time period (e.g., seasonality, macroeconomic shocks, and secular trends in entry and exit). Finally, we also control for the total generation by PJM units appearing in the CEMS data. Combined with the control for total demand, this is equivalent to controlling for total demand net of nuclear, solar, wind, biomass, and other renewable or non-CEMS generation.

Regression results. We first show regression results aggregated by technology type, in Table 2 (coefficients on control variables are shown in the Online Appendix Table A6). We see that

³² For expositional purposes, we focus on generation aggregated up to a prime mover type (e.g., boiler) or a fuel type (e.g., coal), but the regression analysis could also be done at the individual unit level.

³³ Clustering by week accounts for serial correlation in unobservables, such as an exogenous multi-day outage at a plant.

³⁴ Specifically, we use the day-ahead forecasted peak load in hours for which the peak regulation requirement applies (4 a.m. to midnight) and set the variable equal to zero in off-peak hours. Similarly, we use the day-ahead forecasted valley load in hours for which the off-peak regulation requirement applies (midnight to 4 a.m.) and set the variable equal to zero in peak hours.

³⁵ We also include a peak versus off-peak hour dummy variable.

³⁶ Demand data are from PJM. Natural gas, oil, and coal prices are from the Energy Information Administration. Weather is from NOAA. See Online Appendix for details.

TABLE 2 The Impact of the Regulation Requirement on the Energy Market

	Boiler (MWh)	CC (MWh)	CT (MWh)	Other tech. (MWh)
Regulation requirement, 100 MW	-388.9** (189.7)	357.1** (162.4)	16.2 (208.6)	15.5 (22.1)
Observations	19,693	19,693	19,693	19,693
Within R ²	0.91	0.71	0.49	0.13
Mean of dep. var.	40,185	14,290	848	554

Note: This table shows estimates from four separate time-series regressions. In all columns, the dependent variable is total MWh of electricity generated per hour in the PJM market by units that appear in CEMS data (where each column aggregates across all units of a particular type). Coefficients on control variables are shown in the Online Appendix, Table A6. The unit of analysis is an hour. Standard errors are clustered by sample week. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

TABLE 3 The Impact of the Regulation Requirement on the Energy Market

	Coal (MWh)	Natural gas (MWh)	Oil (MWh)	Other fuel (MWh)	CO ₂ (tons)
Regulation requirement, 100 MW	-351.0 (234.3)	432.6** (192.9)	-97.7 (68.2)	16.1 (22.0)	-242.4*** (89.0)
Observations	19,693	19,693	19,693	19,693	19,693
Within R ²	0.88	0.82	0.46	0.13	0.98
Mean of dep. var.	39,818	14,906	570	581	45,215

Note: This table shows estimates from five separate time-series regressions. For the first four columns, the dependent variable is total MWh of electricity generated per hour in the PJM market by units that appear in CEMS data (where each column aggregates across all units of a particular fuel type). For the right-most column, the dependent variable is CO₂ emissions (tons) per hour for all PJM units in CEMS (i.e. combining across the four unit types from the first four columns). Coefficients on control variables are shown in the Online Appendix, Table A7. The unit of analysis is an hour. Standard errors are clustered by sample week. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

when more regulation is required, the unit types providing services in the energy market change, with decreased generation from boiler units and increased generation from combined cycle units. Specifically, for each 100 MW of additional regulation capacity required by the system operator, boiler units decrease their generation by 390 MWh and combined cycle units increase their generation by 360 MWh (both statistically different from zero at the five percent level). The difference between these two comes from a small number of combustion turbines and units with other technology types (right-most columns).

Because different technology types use different primary fuel sources, the results in Table 2 will have implications for fuel use and therefore environmental impacts. We next show regression results aggregated by fuel type, in Table 3. Most PJM boiler units burn coal, although some burn natural gas or oil. Similarly, most combined cycle units and combustion turbines use natural gas, but some use oil. Consistent with the boiler results in Table 2, we see a decrease in coal-fired generation and oil-fired generation in Table 3. Similarly, consistent with the combined cycle results, we see an increase in natural gas generation.

To understand the emissions impact of this change in the generation mix, we can estimate a similar regression with CO₂ emissions as the dependent variable. We now aggregate CO₂ emissions across all units in CEMS. We see in the right-most column of Table 3 that CO₂ emissions fall when the regulation requirement is raised: for every 100 MW increase in the regulation requirement, we estimate 240 fewer tons of CO₂ are emitted by units participating in the energy market, statistically significant at the one percent level. This is in line with the fuel use changes described above. Specifically, the PJM-wide emissions rate for natural gas units (combining CC and CT units) in our sample is 0.42 tons CO₂ per MWh; the emissions rate for coal and other units combined is 0.95. This difference implies that a shift of 400 MWh from coal to gas would

lead to a decrease in CO₂ emissions of around 210 tons, close to our estimate of 240 tons in Table 3.³⁷

Robustness checks. In the Online Appendix, we explore a suite of robustness checks and placebo regressions. We show a number of regressions that include additional controls. For instance, we control for the standard deviation of the regulation requirement over the previous 72 hours—one might be concerned that our main results are driven by the change in the variance of the regulation requirement from the first to second half of our sample, visible in Figure 4. We also show regressions with alternative functional forms and/or non-parametric specifications for the control variables. Next, we collapse to a daily specification to allow for across-hour effects as in Bushnell and Novan (2021). We also show a specification that limits the sample to units that do not retire during our sample period, to ensure that the main results are driven by these non-retiring units as opposed to units that retired (perhaps for secular reasons) over this time period. Next, we calculate alternative standard errors, specifically Newey-West standard errors with a maximum lag length of 168 hours (1 week).³⁸

Across all of these specifications, we estimate fuel use shifts (coal to natural gas), with magnitudes and statistical significance comparable to what we display in Tables 2 and 3. We also estimate a negative and statistically significant impact of the regulation requirement on CO₂ emissions. We also show more parsimonious regressions, for which we estimate qualitatively similar results but where, not surprisingly, we lose precision.

Additional regressions in the Online Appendix show estimated effects at a number of placebo units (Table A12). We run our primary regression using generating units in nearby states that do not participate in the PJM wholesale energy market.³⁹ We also separately use CEMS-reporting units that are classified as part of commercial or industrial operations; this includes generation from facilities such as hospitals and petroleum refineries. We also estimate our main specification with wind generation as the dependent variable. Finally, we consider a “residual” category of generation as the dependent variable. Following Davis and Hausman (2016), we estimate the effects of the regulation requirement on the amount of generation that would be needed to satisfy total demand, after accounting for the generation quantity reported in CEMS. This category accounts for nuclear generation, hydro generation, net imports, and small units not reported in CEMS. Across all but one of these categories, we estimate only small effects of the regulation requirement. For the non-PJM coal units, we estimate a larger effect, but it is noisy and has the *opposite* sign of the coal estimates in Table 3.

We also estimate a series of two-way fixed effects regressions, in which the plants in nearby states serve as “control” units, allowing us to include day-of-sample effects. Results are qualitatively similar, with comparable point estimates.⁴⁰

³⁷ The difference between this back-of-the-envelope calculation and our estimate may be due to differential heat rates of marginal versus average units, and/or to a heat rate effect of regulation provision that we describe in the Online Appendix.

³⁸ If there is cross-day correlation, then a rule of thumb like $N^{1/4}$ (in this case = 12 hours) would be insufficient, so we use a more conservative lag length.

³⁹ Specifically, our full dataset contains data on all CEMS units in Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, North Carolina, New Jersey, Ohio, Pennsylvania, Tennessee, Virginia, Washington DC, and West Virginia. These states are covered in part by PJM. However, in states such as Indiana, only a minority of the plants participate in the PJM market, with the rest primarily participating in the MISO wholesale market. Our placebo sample consists therefore of, for example, MISO-participating units in states such as Indiana.

⁴⁰ This two-way fixed effects specification does not serve as our main specification for a couple of reasons, as described in the Online Appendix. Even in this specification, our primary source of identification is the switch from a varying regulation requirement in the first half of the sample to a flat requirement in the second half. Thus “control” units in other states are not expected to provide much additional help with identification. The time-series specifications are a more transparent way to implement this identification strategy. The two-way fixed effects can help if there additional regional or national secular trends that are not adequately controlled for, and as such it is reassuring that they yield qualitatively similar estimates.

Overall, our empirical estimates show that when more frequency regulation is needed, substantial fuel use changes occur in the energy market. In particular, coal units sell less in the energy market and natural gas units sell more. This leads to an overall decrease in CO₂ emissions, holding generation constant. This magnitude is quite large—why would a 100 MW change in the regulation market lead to a roughly 400 MWh change in the energy market? Our simulated model suggests that this could occur if unit behavior around minimum constraints is changing. To further understand the magnitude and the mechanism behind it, we turn to regressions that incorporate information about minimum and maximum constraints.

6. Evidence of changes along extensive versus intensive margins

■ To further connect our modeling results to our empirical results, we next estimate various intensive versus extensive margin changes. We separate hourly generation into five bins for each unit: *Off*, *Below Minimum Constraint*, *At Minimum Constraint*, *Between Minimum Constraint and Maximum Capacity*, and *At Maximum Capacity*. Then we count the number of units of each fuel type in each bin in each hour, giving us a time series of bin-level counts for each fuel type. Details of the data and variable construction are in the Online Appendix.

We regress the count of generators falling into each bin on the regulation requirement and a vector of controls separately for each fuel/mover type. The regressions take the form:

$$N_{i,t} = \alpha_i + \beta_i R_t + X_t \Theta_i + \varepsilon_{i,t}, \quad (3)$$

where $N_{i,t}$ is a count of units of fuel type i in hour t that have generation levels falling in a particular bin (e.g., the number of coal boiler units at 5 a.m. on November 1, 2012 with capacity factors below their minimum constraint). Again R_t is the regulation requirement and X_t is a vector of controls (the same controls as in the generation regressions above). Standard errors are clustered by sample week.

Table 4 shows the results of these regressions for each of the three units types of interest: boiler, combined cycle, and combustion turbine (results for “other” units are shown in the Online Appendix Table A14). These effects are in line with both the generation changes shown in Table 2 and with the stylized model. Panel A shows that boilers are less likely to be at their maximum (Column 5) and more likely to operate within their main operational range (Column 4) when the regulation requirement is higher. Specifically, a 100 MW increase in the regulation requirement causes one fewer units to be at maximum capacity. This is consistent with this unit providing additional regulation, and needing its set point to be below its maximum to have the flexibility for upward movements in response to a regulation signal. It is also consistent with the boiler decreasing its energy provision to accommodate additional energy provision by combined cycle plants, discussed next.

Panel B shows that combined cycle units are more likely to be dispatched when the regulation requirement is higher. For every 100 MW additional regulation requirement, around two combined cycle units are more likely to be dispatched and in their main operational range (Column 4). This could be consistent either with dispatching with positive generation to be able to themselves provide frequency regulation, or with needing to fill a gap left by reduced boiler generation, shown in Panel A.

Panel C shows that combustion turbines are also more likely to be operating within their main operational range, some combination of units being less likely to be off (Column 1) or less likely to be at their maximum capacity (Column 5). This could be because they move to the middle of their range to provide frequency regulation, because they are newly dispatched to fill in for lost boiler generation, or some combination of both.

As shown in the Online Appendix, results are robust to an alternative construction of the minimum constraint variable. Results are also robust to using ten bins, identically spaced across the capacity of each unit (0–10% of capacity, 11–20% of capacity, etc.), rather than a minimum constraint definition.

TABLE 4 The Regulation Requirement and Extensive Versus Intensive Margins

Panel A. Boilers	Off	Below min	At min	Above min	At max
Regulation requirement, 100 MW	-0.29 (1.03)	0.20 (0.16)	0.39 (0.40)	1.18 (0.90)	-1.48*** (0.47)
Observations	19,693	19,693	19,693	19,693	19,693
Within R ²	0.71	0.11	0.38	0.43	0.75
Mean of dep. var.	199	5	11	99	29
Panel B. Combined Cycle Plants	Off	Below min	At min	Above min	At max
Regulation requirement, 100 MW	-2.33*** (0.86)	0.03 (0.25)	0.40* (0.24)	2.31*** (0.70)	-0.40 (0.25)
Observations	19,693	19,693	19,693	19,693	19,693
Within R ²	0.64	0.22	0.07	0.61	0.32
Mean of dep. var.	56	13	9	55	2
Panel C. Combustion Turbines	Off	Below min	At min	Above min	At max
Regulation requirement, 100 MW	-2.13 (3.38)	0.01 (0.46)	0.31 (0.33)	3.06 (2.44)	-1.26** (0.59)
Observations	19,693	19,693	19,693	19,693	19,693
Within R ²	0.48	0.31	0.27	0.45	0.19
Mean of dep. var.	410	3	1	8	1

Note: This table shows estimates from 15 separate regressions. The dependent variable is a variable representing the count of units of each type generating at each level in PJM. The unit of analysis is an hour. Effects for other unit types are shown in the Online Appendix, Table A14. Standard errors are clustered by sample week. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

Overall, the primary effect we see when the regulation requirement is higher is that more units operate within their main operational range, rather than being off or at the maximum constraint. This is consistent with the model in Section 3. The magnitudes are also consistent with a back-of-the-envelope calculation of the number of units that would be needed to provide 100 MW of regulation. Recall that the typical unit can commit 10–20% of its capacity to regulation. In our sample, the average boiler or combined cycle unit has a capacity of around 230–280 MW, implying that two to four units would be needed to provide 100 MW of regulation. Combustion turbine units in our sample have a capacity of around 80 MW, so more of these plants would be needed to provide the same amount of regulation.

We see empirically that generators behave in intuitive ways along both the intensive and extensive margins when the regulation requirement is exogenously changed. Because they are multi-product firms, they adjust their outputs in multiple markets. Indeed, recall that one of the motivations behind the policy changes to the regulation requirement was to free up capacity for the energy market (Section 5). Moreover, minimum and maximum constraints can lead to changes in the energy market that are outsized in comparison with the change in the regulation requirement.

7. Discussion

■ In this section, we discuss several broader implications of our results. First, as described in Section 5, we find CO₂ impacts resulting from changes in frequency regulation requirements. Specifically, for every 100 MW increase in the regulation requirement, we estimate a decrease of 240 tons of CO₂ per hour. This represents a decrease of 0.5% of CO₂ emissions, or an annual total of 2 million tons of reduced CO₂. Valued at the IWG Social Cost of Carbon, the short-term generation changes from an increase in the regulation requirement would reduce

climate damages by around \$90M per year.⁴¹ Recent peer-reviewed estimates would place the value even higher (Pindyck, 2017; Moore et al., 2017; Ricke et al., 2018; Bastien-Olvera and Moore, 2020).

A full welfare analysis would compare these emissions impacts to changes in fuel costs, operations and maintenance costs, and the external costs associated with other pollutants (such as particulate matter and sulfur dioxide). We do not attempt this calculation because we do not observe operations and maintenance (O&M) cost data across units or across time. Changes in frequency regulation provision would be expected to impact wear-and-tear on the plant, and therefore O&M costs. Similarly, changes in plant utilization (e.g., capacity factors) would also be expected to impact O&M costs. Moreover, changes to regulation requirements also impact the grid in hard-to-quantify ways relating to resilience and the probability of blackouts in rare events.

However, we note a few things. First, we would expect that an increase in the regulation requirement would lead to an increase in total overall costs, as regulation provision is costly. For our four-unit model in Section 3, total costs (combining energy provision and regulation provision costs) increase with the regulation requirement. Whether these private cost increases outweigh the emissions cost savings described above is an empirical question. For the time period we study, we observe a typical coal price of \$2.34 per mmbtu and a natural gas price of \$4.71 per mmbtu.⁴² Supposing a coal heat rate of 10.3 MWh per mmbtu and a natural gas heat rate of 7.7 MWh per mmbtu, this would imply that a 400 MWh change from coal to natural gas from an increased regulation requirement would cost around \$5000 per hour in increased fuel costs (again, note this ignores changes in O&M costs).⁴³ In contrast, the CO₂ reductions would save over \$10,000 per hour in external climate damages. In short, because coal is so much more CO₂-intensive than natural gas, the private cost changes could easily be outweighed by the external cost changes.

Second, our results on frequency regulation markets have implications for utility-scale battery storage. There is a growing interest in using energy storage, including batteries, flywheels, and loads coordinated to behave like storage, to help operate the electrical grid. The energy economics literature has focused on the use of batteries for arbitrage: charging when demand is low (e.g., at night) and discharging when demand is high (e.g., the late afternoon). However, batteries can also be used to provide ancillary services such as frequency regulation (Department of Energy, 2013; International Renewable Energy Agency, 2017; Deloitte, 2018; Ryan et al., 2018). PJM has been at the forefront of incorporating storage into ancillary service markets; storage providers found RegD particularly lucrative when it was first introduced.⁴⁴ Indeed, nearly all storage capacity in PJM is built for the provision of frequency regulation.⁴⁵

Consider a battery entering the market in order to participate in the regulation market. Suppose this battery is inframarginal—batteries generally have high fixed costs but low marginal costs—and suppose that the battery does not participate in the energy market (recall from above that batteries in PJM generally do not provide arbitrage in the energy market). If this battery participates in each period, its entry represents a reduction in the residual regulation requirement faced by conventional generators, by a magnitude equal to the capacity of the battery. Based on our analysis of the PJM regulation market, we expect that the entry of batteries in PJM would lead to generation mix changes and emissions changes in the energy market. For the time period

⁴¹ We use the 2015 SCC from the Interagency Working Group on Social Cost of Greenhouse Gases (2016) and convert to 2019 dollars using the CPI, implying a value of \$44 per metric ton.

⁴² Source: EIA's "Average cost of fossil fuels for electricity generation."

⁴³ If we include oil costs, we would estimate *decreased* fuel costs, as oil prices paid by generators are over \$20 per mmbtu, and we show a negative albeit very noisy estimate on oil-fired generation in Table 3.

⁴⁴ See Maloney (2017), "Is the bloom off the RegD rose for battery storage in PJM?" in *Utility Dive*, <https://www.utilitydive.com/news/is-the-bloom-off-the-regd-rose-for-battery-storage-in-pjm/503793/>.

⁴⁵ 22 of PJM's 27 facilities list "frequency regulation" as a service; only five facilities list "load management" and just one lists "arbitrage" as a service, according to Energy Information Administration data. Source: EIA-860 data for 2018.

we study (2012-2014), we could infer that battery entry (akin to a reduction in the regulation requirement) would lead to *increased* CO₂ emissions, with a gas to coal shift. This provides empirical support for simulation evidence in the engineering literature. Specifically, Ryan et al. (2018) uses a unit commitment and dispatch model of a small power system, not calibrated to PJM, to show the life-cycle environmental impacts of batteries. That research similarly finds fuel switching effects for conventional generators when batteries are introduced to provide frequency regulation.⁴⁶

In sum, our results have qualitatively important implications for climate policy and for battery deployment. The generation mix changes that could result from frequency regulation changes will have impacts on CO₂ emissions. A few brief caveats are worth noting. Recall that in the stylized model, we see that the changes in regulation can have many potential impacts on the energy market. Thus, the mechanisms we describe will be broadly relevant, but our specific regression results are not necessarily externally valid: the results cannot be simply extrapolated to alternative time periods in PJM nor to other system operators. Different fuel costs or the secular retirements of power plants could mean very different impacts of changes to the regulation market.^{47,48} In addition, the introduction of batteries could enable additional renewables entry,⁴⁹ which could lower CO₂ emissions. The introduction of carbon pricing would also be expected to change the relationship between ancillary services and energy markets. Future empirical work in these areas will be important as the electrical grid continues to evolve.

8. Conclusion

■ Overall, we see that changes in the structure and makeup of the frequency regulation market impact generators that participate in the energy market. We present a model that allows generators to be multi-product suppliers, additionally making the realistic assumption that units are constrained by non-zero minimum and maximum constraints. With these assumptions, we show that policy and market changes can cause power plants to move from fully off to operating at non-negligible minimum load, and vice-versa. Moreover, our model and results suggest that generating units should be thought of as multi-product firms participating in multiple markets, and that the concept of a “marginal” firm is much more complex after considering both minimum constraints and multiple markets.

Turning to empirical estimation for the PJM market, we show that for every additional 100 MW increase in frequency regulation required of plants in PJM, there is an approximately 360 MWh increased use of combined cycle power plants in the energy market, and a corresponding decrease in the use of boiler units. The results are directionally robust to considering alternative controls and various alternative specifications. Results also pass a series of placebo tests using generators outside of the PJM market. However, the magnitudes and even the direction of the effects are specific to the time period and market we study – as our theoretical model shows, the

⁴⁶ We also expect two additional impacts of battery entry. Battery entry can impact the heat rates of conventional generators, similar to how frequency regulation impacts the heat rate, a point we discuss in Section 2 and in the Online Appendix. Furthermore, we note that batteries are net users of electricity (they do not have 100% round-trip efficiency), and so their entry impacts the amount of conventional power plant generation required (Department of Energy, 2016). This mechanism is not captured with the regression approach we have taken, which conditions on total quantity demanded across the system.

⁴⁷ For related mechanisms in the context of wind energy, see Callaway et al. (2018); in the electric vehicle context, see Holland et al. (2016a, 2016b).

⁴⁸ The fact that we see non-linearities in the model in Section 3 suggests that even *within* a given geographic region or broad time period, one might expect to see heterogeneity in the impact of a change to the regulation requirement across different levels of demand or different *ex-ante* levels of the regulation requirement itself. Unfortunately, we have insufficient power for exploring this heterogeneity ourselves. However, future work could look at this in depth with either additional sources of identifying variation or with additional simulations calibrated to various markets.

⁴⁹ For research on the interaction of renewables and storage, see Gowrisankaran et al. (2016); Ovaere and Gillingham (2019), and Karaduman (2021).

results depend on the composition of generators operating in the market (and therefore on fuel prices, etc).

Most importantly, this research demonstrates that ancillary services markets and energy markets are far more intertwined than economics researchers might have previously thought. The structure and policy details of ancillary service markets have important impacts for generators and for the energy market, and more careful research across the country is necessary to better understand these complexities in different settings. Future economics research could use structural methods to estimate power plant costs in both markets and evaluate market power after accounting for the existence of both minimum constraints and multiple markets. Future work could also incorporate dynamic constraints (e.g., minimum up and down times) and transmission constraints. Finally, we have focused on short-term impacts. If regulation market changes impact profitability and therefore retirement decisions, long-term effects could differ.

We also find that regulation market changes can impact the fuel mix in the energy market and therefore CO₂ emissions. Our results are specific to a second-best world in which CO₂ emissions are not priced. This has policy importance as the grid continues to evolve to mitigate climate change (e.g., by incorporating renewables). How batteries, renewables, and conventional power plants will interact in markets for both generation and grid reliability will continue to be an important question, pointing toward the complexities inherent in designing second-best greenhouse gas abatement policy.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table A1: Four-Unit Model

Table A2: Total Annual Generation by Unit Type, CEMS Data, 2012-2014

Table A3: Total Annual Generation by Fuel Type, EIA Data, 2012-2014

Table A4: Simulated Dataset to Illustrate the Identification Strategy

Table A5: Summary Statistics

Table A6: Displaying Control Coefficients: The Impact of the Regulation Requirement on the Energy Market

Table A7: Displaying Control Coefficients: The Impact of the Regulation Requirement on the Energy Market

Table A8: Parsimonious Robustness Check: The Impact of the Regulation Requirement on the Energy Market

Table A9: Parsimonious Robustness Check: The Impact of the Regulation Requirement on the Energy Market

Table A10: Robustness to Alternative Specifications: The Impact of the Regulation Requirement on the Energy Market

Table A11: Alternative CO₂ Measurement: The Impact of the Regulation Requirement on the Energy Market

Table A12: Placebo and Residual Units: The Impact of the Regulation Requirement on the Energy Market

Table A13: Specifications with Two-Way Fixed Effects

Table A14: Showing Other CEMS Units: The Regulation Requirement and Intensive/ Extensive Margins

Table A15: Alternative Minimum Constraints Data: The Regulation Requirement and Intensive/ Extensive Margins

Table A16: Bins: The Regulation Requirement and Intensive/Extensive Margins

Figure A1: Treatment Variable for Simulation of Identification Strategy

Figure A2: Monthly Generation

Figure A3: Minimum Constraints