The Effect of Zero Emission Credits in Illinois and New York on Wholesale Power Market and Environmental Outcomes*

David B. Adler (Carnegie Mellon University)
Lynne Kiesling (Carnegie Mellon University)

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Abstract

Nuclear power plants are facing financial challenges in competitive wholesale power markets due to three coinciding factors in the mid-2000s: falling natural gas prices and increased natural gas generation capacity, increases in wind generation capacity arising from renewable portfolio standard (RPS) regulations, and stagnant electricity demand. New York and Illinois have implemented new regulations requiring utilities and load-serving entities to purchase Zero Emission Credits (ZECs), with proceeds returned as revenue to participating nuclear power plants. We use a difference-in-differences regression analysis to examine ZEC program effects on generation, wholesale and retail prices, and air quality. We find that nuclear generation increased in both states as a result of the ZEC programs, increasing renewable generation in Illinois and reducing coal generation in New York. Wholesale prices fell in both states, and retail prices fell slightly in Illinois and rose in New York. Finally, we find local air quality improvements in both states, as well as a significant short-run decrease in carbon dioxide emissions in New York.

Keywords: Nuclear power, clean energy standard, zero emission credits, renewable portfolio standard, electricity markets

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1 Introduction

After being the least-cost source of much of the electricity generated in some regions of the United States for three decades, the nuclear power industry encountered a trifecta of dynamic shocks to their business model in the mid-2000s. The shale gas revolution post-2008, induced by technological change and an institutional environment conducive to innovation, reduced natural gas prices and led to increased natural gas generation competing with nuclear generators in organized wholesale power markets (Hausman and Kellogg, 2015).

At the same time, regulatory changes in the form of renewable portfolio standards (RPS) in 30 states and the District of Columbia gave an impetus to investment in wind generation capacity, also competing with nuclear generation (Schmalensee, 2012). Regulatory polices to induce investment in renewable generation were designed for scenarios in which renewable generation is more costly than traditional generation (Garcia, Alzate and Barrera, 2012). Due in part to the success of such policies, the leveled cost of electricity (LCOE) for wind fell below that of coal around 2010, and by some estimates the LCOE of both wind and solar is now lower than combined-cycle natural gas. At the same time, the LCOE for nuclear generation has increased due to higher operating and maintenance costs.

Finally, the demand for electricity fell in 2008-2009 during the recession associated with the financial crisis, and demand has largely stagnated since then. These three changes have squeezed profit margins in nuclear generation and have transformed the wholesale power markets in which half of the U.S. nuclear power plants participate. For 30 years the institutional design of wholesale power markets has grappled with a complicated portfolio of regulatory issues arising from the combination of constructing new rules for nascent markets and adapting to evolving environmental regulations (Bushnell, 2010; Chao, 2011). In the U.S., electricity generation accounted for 26.9% of greenhouse gas emissions in 2018, a decrease from 29.1% in 1990 (U.S. Environmental Protection Agency, 2020). The generation portfolio fuel mix has changed and decarbonized over the 30 years of organized wholesale power markets, with considerable investment in natural gas generation investment occurring in those markets (Energy Information Administration, 2020).

These changes in costs for natural gas and renewable generation have resulted in declining average market prices and in lower market prices in periods when nuclear plant owners could earn considerable marginal revenue. When nuclear plants are dispatched they receive lower prices on average, and they are dispatched less frequently because wind's lower marginal cost (and ability to submit negative bids due to the incentives embedded in the production tax credit) can put wind in front of nuclear in merit-order dispatch in some off-peak hours (Jenkins, 2018).

With growing attention to decarbonization and reducing the climate impact of electricity generation, nuclear generation would seem to have an advantage compared to fossil fuel technologies like coal and natural gas. Yet under existing market rules and environmental regulations, nuclear generation falls in a gap between RPS-induced resources with near-zero marginal cost and the downward price pressures of natural gas generation. Several states, most notably New York and Illinois, have revised their RPSs into clean energy standards, in which nuclear resources can earn Zero Emission Credits (ZECs) on the energy they generate and sell. By regulatory requirement, load-serving entities must purchase ZECs for specific percentages of the electricity they sell, with participating nuclear plant owners receiving the proceeds. Haratyk describes the ZEC design and its focus on the near-zero-carbon attribute of nuclear power (2017, pp. 160-161).

How has this regulatory change affected outcomes in the markets in which these resources participate? We examine whether the ZECs regulation has affected the composition of the generation fuel mix and the wholesale and retail market prices, as well as the effects on levels of carbon dioxide and three criteria pollutants: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and small particulate matter ($PM_{2.5}$). Using monthly data from the Energy Information Administration (EIA), the Environmental Protection Agency (EPA), and the regional transmission organizations that operate the relevant wholesale power markets (MISO, NYISO, PJM), we perform a difference-in-differences analysis to identify the economic and air quality effects of the ZEC regulations in Illinois and New York.

Our analysis contributes to the electricity literature by estimating the economic and environmental effects of this novel regulatory instrument. We build on research on the economic and environmental effects of nuclear plant closures (Davis and Hausman, 2016; Severnini, 2017), of shale gas supply on natural gas prices (Joskow, 2013; Hausman and Kellogg, 2015; Linn, Muehlenbachs and Wang, 2014), and of the ensuing substitution of natural gas generation for coal generation (Knittel, Metaxoglou and Trindade, 2015; Fell and Kaffine, 2018). This paper also extends the research on the economics of nuclear power plants in liberalized power markets (Linares and Conchado,

2013) and nuclear plant retirements in such markets (Haratyk, 2017).

We find that the ZEC program was designed slightly differently and had different effects in the two states, with the differences largely a consequence of differences in generation portfolios. Both states use an administratively-determined quantity of ZECs and a price equal to the federal estimate of the social cost of carbon as a baseline; the Illinois ZEC program incorporates wholesale power market feedback effects into the ZEC price, while the New York program's feedback effects use forecasted prices. In both states nuclear generation increased after both the announcement and start of the ZEC program. In Illinois the ZEC program was associated with a decrease in natural gas generation, while in New York the ZEC program led to a reduction in coal-fired generation. In both states we find evidence that the ZEC program led to a reduction in wholesale power prices, although we find differing impacts on retail prices. In Illinois we find a short-term reduction in residential retail prices due to the ZECs program, suggesting a pass-through of the reduction in wholesale prices, while in New York we see a significant increase in retail pricing that could be attributable to a pass-through of the cost subsidy. In both states we see short-term improvements to local air quality due to the ZECs program, and in New York we find signification reductions in short-run carbon dioxide emissions.

The paper proceeds as follows. Section 2 summarizes the economics driving the market pressure on nuclear plants and provides background on the institutional details of the clean energy standards implemented in New York and Illinois. Section 3 presents the conceptual framework as well as the empirical strategy derived from it. Section 4 describes the data used in the analysis and discusses some descriptive statistics. Section 5 reports and discusses the results. Lastly, Section 6 concludes.

2 Motivation and Background

As a product, electricity has several beneficial attributes. Its generation and consumption also produce emissions of pollutants as unintended by-products. The institutional framework – market design and regulation – of a wholesale power market affects how value and cost attributes shape market outcomes. Market rules determine which product attributes are reflected in transactions, and the equilibrium prices in those markets determine the profitability of large, baseload nuclear plants with high capacity utilization.

2.1 Wholesale Power Market Design and Environmental Regulation

Wholesale power markets focus on the value of the energy in direct use, within an economic and environmental regulatory context. Wholesale market designs generally do not directly reflect the greenhouse gas/carbon footprint of the energy transacted in these markets, although some environmental and economic regulations affect their incentives and outcomes.

Wholesale power market outcomes have led to financial pressure on nuclear power plants due to three coinciding factors in the mid-2000s: falling natural gas prices and increased natural gas generation capacity, increases in wind generation capacity arising from renewable portfolio standard (RPS) regulations, and stagnant electricity demand. Natural gas plants are frequently the marginal supply unit, so their short-run marginal cost sets market prices in many hours; as natural gas prices fall they reduce wholesale market prices paid to all dispatched units, including nuclear plants (Joskow, 2013; Davis and Hausman, 2016; Linn, Muehlenbachs and Wang, 2014). In their analysis of the San Onofre nuclear plant closure in 2012, Davis and Hausman show the dramatic decline in nuclear industry profitability dating to 2008 (Davis and Hausman, 2016, Figure 1, p. 96). At that time, fracking started to increase shale gas supply and natural gas prices fell by 50 percent (Hausman and Kellogg, 2015).

Natural gas generation has substituted for substantial amounts of coal-fired generation, with a resulting reduction in greenhouse gas emissions (Fell and Kaffine, 2018; Knittel, Metaxoglou and Trindade, 2015). Fell and Kaffine (2018) use generation unit-level data to show that the combination of falling natural gas prices and increased wind generation reduced the supply of coal in organized wholesale power markets, and together they account for the observed decline in carbon dioxide emissions from 2007-2013. But falling natural gas prices that have enabled the coal substitution have also contributed to falling nuclear revenues (Jenkins, 2018), which could diminish carbon dioxide emission reductions in the future.

Thus nuclear plant owners face two types of supply-driven pricing pressure in wholesale power markets. First, falling natural gas prices have put downward pressure on wholesale market prices, reducing the producer surplus that yields nuclear plant profits.[1] Second, as investment in large-scale wind and solar generation have increased and

[1]As Davis and Hausman (2016) note, "Nuclear plants continue to have lower marginal cost than coal and gas plants and thus are still near the bottom of the supply curve. Instead, what has changed

they have become more cost effective, those resources have also put downward pressure on market prices and occasionally displaced nuclear plants at the bottom of the supply curve in the hours when nuclear plants typically earned the revenue that enabled them to cover their operating and maintenance (O&M) costs, which are substantially higher than those for other fuel sources.

The fundamental economic driver of this pressure in competitive wholesale power markets is differences in the short-run marginal cost of generating energy using different technologies: $\mathrm{MC}_{ng} > \mathrm{MC}_{nuclear} > \mathrm{MC}_{renew}$, which is approximately zero. Wholesale power markets operate by constructing market supply curves for generation at various time scales (e.g., 15-minute, hourly, day-ahead), based on offers that generators submit.[2] The offers in competitive wholesale power markets thus generally reflect short-run marginal cost, and the uniform-price auction market design of wholesale power markets enables all dispatched units to earn producer surplus (except for those with marginal cost equal to the market-clearing price). In the pre-2008 markets, with $\mathrm{MC}_{ng} > \mathrm{MC}_{coal} > \mathrm{MC}_{nuclear}$, nuclear plants running almost continuously were the least-cost technology for providing baseload generation. With the fall in natural gas prices, the reduction in coal capacity, and the increase in wind capacity, those short-run supply curves look very different today. Nuclear plants are no longer assured of being least-cost and therefore dispatched first or to full capacity. Thus in some hours when nuclear plants used to earn their profit from the market-clearing price exceeding their marginal cost, wind generators can now outbid them. Jenkins (2018) analyzed these three drivers (falling natural gas prices, increasing wind capacity, stagnant demand) of PJM prices and found that natural gas price declines were the dominant drive of lower market prices; the effects of wind were smaller and concentrated in PJM's western region, adjacent to states with higher wind capacity. U.S. nuclear industry revenue was \$39.5 billion in 2009, and decreased to \$36 billion a decade later (IBISWorld, 2020). This 8.9 percent fall in total revenue over the decade ran counter to historical expectations about the profitability of low-emissions baseload generation. Over the same decade nuclear power generation increased slightly from 799 to 809 terawatt-hours, or

is the ability of hour-to-hour net revenues to cover the fixed costs of keeping a nuclear plant open." (pp. 97-98).

[2] Fell and Kaffine (2018) Section 1 provides an illustration of supply curves and security-constrained economic dispatch in wholesale power markets. They explain how changes in the generation technology mix change the supply curve according to short-run marginal cost, and thus change which units get dispatched and earn revenue.

was roughly even as a share of total electricity demand.[3]

In this new market context nuclear plants are also at a disadvantage because they lack the flexibility to complement wind generation, which has become an increasing share of the generation portfolio over the past decade. Natural gas and renewable generation are complements in production because fast-ramping, energy efficient combined-cycle natural gas turbines can provide backup for unexpected declines in wind or solar generation, and can also spin up quickly to provide energy in the late afternoon in places like California that have considerable distributed solar generation whose production falls at the same time. Nuclear's slow ramping rate and high cost of ramping generation up and down is less compatible with the value of such flexibility.

Changes in regulatory institutions have contributed to this increase in wind power. Owners of generation plants are subject to environmental regulation, largely in the form of requirements to meet the National Ambient Air Quality Standards (NAAQS) for the criteria air pollutants defined by the Environmental Protection Agency (EPA). In 2014 the EPA proposed the Clean Power Plan as a mechanism for regulating greenhouse gas emissions under the Clean Air Act, but it was not implemented.[4] Legislative attempts over the past two decades to pass federal carbon policy, in the form of either a carbon tax or emissions permit trading, have not succeeded. Some regional carbon policies have emerged, such as California's carbon tax and the Regional Greenhouse Gas Initiative (RGGI) in the Northeast.

In this regulatory landscape, climate policy has occurred primarily at the state level, with renewable portfolio standards (RPSs) as a primary regulatory mechanism. As of 2020, 30 states and the District of Columbia have passed RPSs establishing targets for the amount of electricity sold in a state being generated using renewable resources. RPSs are policy mechanisms to create incentives to invest in renewable energy generation capacity. Wind power has also received a federal production tax credit in recent years (with some brief lapses), further boosting investment incentives and enabling wind to underbid other resources in wholesale power markets.

Nuclear plants fall in a gap in this regulatory landscape that runs counter to the stated policy objective of greenhouse gas emission reduction. While nuclear power

[3] Furthermore, Linares and Conchado (2013) develop a break-even investment cost analysis and find that nuclear plants are not cost-competitive in liberalized power markets.

[4] The Supreme Court of the United States issued a stay of the Clean Power Plan on February 9, 2016, until all lower courts had heard and ruled on the various legal challenges to the proposal. In the ensuing period, the U.S. Presidential election led to a change of political party, resulting in policy changes at many federal administrative agencies including the EPA.

has a history of concern over radioactive waste (and notable accidents like Chernobyl and Fukishima), it is also the most energy-dense technology for generating near-zero emission energy at a large scale. In some U.S. regions, nuclear generation has supplied much of the baseload generation since the 1980s. As of 2019, nuclear generation made up roughly 20 percent of total net generation in the U.S.[5]

The third factor in the financial pressure on nuclear plants is stagnant demand for electricity, which has grown at only 1 percent annually since 2000 (Energy Information Administration, 2020).[6] Given these shifts in the market value of nuclear generation, the absence of a revenue stream accruing to its carbon-free attribute has risen in importance.

2.2 Clean Energy Standards in New York and Illinois

The prospect of nuclear plants closing due to economic pressures has raised concerns for two reasons. First was the aforementioned policy objective of reducing greenhouse gas emissions and meeting state RPS targets. Second was reliability, which with safety and affordability has been a top regulatory priority since the beginning of public utility regulation in the early 20th century. With growing wind capacity, the potential closure of nuclear plants raised the possibility of substituting an intermittent source of power for one that had provided baseload generation reliably for decades. States with competitive wholesale power markets have fewer regulatory mechanisms to require nuclear plants to operate (and to pass the costs on to customers).

New York and Illinois have created a new regulatory instrument to attenuate the revenue problem for nuclear plants operating in their competitive wholesale power markets. Both New York and Illinois are restructured states, which means that in the 1990s they implemented changes to allow both wholesale and retail market competition.[7] Regulatory restructuring involved regulated utilities unbundling generation from the vertically-integrated firm. Utilities either sold their generation units to independent power producers or created generation affiliates. The 5 nuclear plants affected by the ZECs regulations (3 in New York and 2 in Illinois) are owned by Exelon Generation, a subsidiary of Exelon and an affiliate of the 6 distribution utilities also owned by Exelon

[5]U.S. Energy Information Administration: `https://www.eia.gov/tools/faqs/faq.php?id=427&t=2`.

[6]See Table 7.6 in EIA's Monthly Energy Review.

[7]Illinois implemented restructuring through legislation, while in New York restructuring was implemented through the Public Service Commission without legislation.

(Comed, PECO, BGE, Pepco, Delmarva Power, and Atlantic City Electric).[8]

This unbundling enabled both independent and affiliated generators and the incumbent distribution utilities to participate in wholesale power markets as sellers and buyers, respectively. New York utilities purchase energy in a single wholesale market operated by the New York Independent System Operator (NYISO), while two different wholesale markets operate in Illinois: Ameren participates in the Mid-continent Independent System Operator's market (MISO) in the southern portion of the state, and Comed participates in PJM's market in the northern portion of the state. Regulatory restructuring also involved lowering barriers to retail competition for all customer classes, including residential customers, although both states retained fixed-price incumbent default service as part of restructuring's political compromise (Kiesling, 2014).

New York implemented a renewable portfolio standard in 2004, with a renewables target of 25 percent by 2013 that was later revised to 30 percent by 2015. In the 2016 order that created ZECs, the Public Service Commission increased the renewables target to 50 percent (then increased to 70 percent in 2019) and a 100 percent emissions free target by 2040 (National Conference of State Legislators, 2020). In 2008, New York assisted in establishing the Regional Greenhouse Gas Initiative (RGGI) with 8 other states. RGGI set a cap on greenhouse gas emissions from electricity generation and enabled emission permit trading in the region. RPS and RGGI participation led to construction of new wind capacity in New York; by 2017 wind's share of annual generation had grown from a negligible amount to over 3 percent (Energy Information Administration, 2020).

The growth in wind generation combined with falling natural gas prices and flat demand put pressure on nuclear generation's financial viability in the state. Despite Governor Cuomo's opposition to fracking within New York State, the effect of fracking (both nationally and in neighboring Pennsylvania) on natural gas supply and prices shifted electricity generation toward natural gas in New York. This shift to greater natural gas and wind generation lowered prices in many market nodes in the NYISO wholesale power market, reducing revenues earned by the three upstate nuclear plants.[9] In November 2015, Entergy said that it would close its James A. FitzPatrick Nuclear Power Plant in Oswego, New York due to "market conditions" as a result of natural gas

[8]The three plants in upstate New York are James A. FitzPatrick, Nine Mile Point, and R. E. Ginna. The two plants in Illinois are Quad Cities and Clinton.

[9]Indian Point Nuclear Plant is located closer to New York City and is in a more transmission-constrained location, so prices there tend to reflect local scarcity and have not fallen as they have in the upstate market nodes.

fracking in neighboring Pennsylvania (Mufson, 2016). Exelon acquired the FitzPatrick plant from Entergy in August 2016; the adoption of a clean energy standard was a major factor in the purchase (World Nuclear News, 2016).

In August 2016 the State of New York Public Service Commission issued an order as part of the state's establishment of a clean energy standard to create the Zero Emission Credit (ZECs) program effective April 1, 2017 (State of New York Public Service Commission, 2016). Under the ZEC program, the New York State Energy Research and Development Authority (NYSERDA) purchases ZECs from the participating nuclear plants in multi-year contracts. Load-serving entities are required to purchase ZECs from NYSERDA, and the required quantity is a function of each LSE's proportion of aggregate retail consumption in each year.[10] The ZEC price is determined administratively using the federal social cost of carbon (SCC) as a reference, increasing through 2029, and adjusted by a formula that reflects both wholesale energy and capacity price forecasts in the NYISO market. Thus the ZEC transactions are administrative and based on forecasted prices, so ZEC prices are not market-determined.[11]

Illinois implemented a voluntary renewable portfolio target in 2001, and revised it into a requirement in 2007 (National Conference of State Legislators, 2020). The target is 25 percent by 2025-2026, and the legislation specifies some technology-specific procurement targets for wind generation, solar generation, and distributed generation. Utilities meet the standard by purchasing renewable energy or renewable energy credits (RECs) based on the amount of energy sold to their default service customers. A cap on REC procurement expenditures exists as a mechanism to limit the effect of RPS requirements on both the retail default service tariff and competitive retail prices. Retail energy providers meet the standard through an administrative delivery charge (Illinois Power Agency, 2017). The Illinois Power Agency (IPA), an agency established in 2007 to implement wholesale procurement to fulfill utility incumbent default service contracts, has the authority to implement the RPS and REC procurement.

As the PJM and MISO wholesale markets evolved after 2007, due both to the growth of natural gas generation and to increased wind generation, nuclear generation

[10] "LSEs comprise all entities serving retail load within a regulated utility territory. This includes investor-owned distribution utilities, energy service companies (ESCOs), Community Choice Aggregation programs (CCAs) not served by ESCOs, and jurisdictional municipal utilities. Retail customers self-supplying through the New York Independent System Operator will also be considered LSEs for this purpose." (State of New York Public Service Commission, 2016)

[11] This design choice was made for legal reasons following the Supreme Court of New York's decision in Hughes that called into question whether it would be legal for a state to adjust actual prices.

owners began to express concern about the economic viability of those large, baseload plants. By 2014, wholesale market prices had changed enough that Exelon was proposing closing at least two nuclear plants in Illinois. Concerns about the potential impacts on reliability, on state-level emissions, and on meeting RPS targets led the Illinois legislature to direct regulatory agencies to prepare analyses of the implications of nuclear power plant closures.[12] Their joint report identified some "market-based" approaches to creating a better alignment between nuclear plant revenues and the environmental attributes of nuclear energy.

After the release of these studies in January 2015, the state legislature and stakeholders entered a comprehensive and contentious process resulting in Illinois Public Act 99-0906, known also as the Future Energy Jobs Act (FEJA). Passed on December 1, 2016, and effective on June 1, 2017, FEJA included provisions for energy efficiency programs, low-income community solar, and energy job creation and training, as well as refinements of the RPS and net energy metering.

For the purpose of our analysis, the most important provision of FEJA was the creation of a Clean Energy Standard implemented through a Zero Emission Credits requirement through 2028. Using its experience from incumbent default service and RPS procurement fulfillment, the IPA is required to procure ZECs from facilities that produce them. Utilities operating in the state (Ameren, Comed, and MidAmerican) are required to purchase them annually from the IPA.[13] The procurement quantity is determined using a historical benchmark: 16 percent of actual electricity delivered to retail customers in 2014. The federal estimate of the social cost of carbon of $16.50 per megawatt hour (MWh) establishes a cap on the ZEC price, and the cap increases by $1/MWh starting in 2023 (Illinois Power Agency, 2017, p. 17). If wholesale market prices move in a direction favorable to nuclear plant revenues, that cap can be reduced. The ZEC price in each annual procurement round is adjusted using a market price index to capture some information about market conditions in that year (Illinois Power Agency, 2017, 23). Thus, while ZEC prices can vary over time the required quantity procured remains unchanged. As with the RPS, the utilities making ZEC purchases have a budget cap on ZEC expenditures, intended to attenuate the impact of ZECs on customer bills. While the ZEC prices are not market-determined, they do incorporate

[12]These agencies included the Illinois Commerce Commission, the Illinois Power Authority, the Illinois Environmental Protection Agency, and the Illinois Department of Commerce and Economic Opportunity (Illinois Commerce Commission et. al., 2015).

[13]In constrast with New York, the ZEC purchase requirement does not include retail energy providers.

market feedback effects from actual prices, while the administrative approach taken in New York incorporates only forecasted prices.

The ZEC programs in both states faced legal challenges from parties claiming that the Federal Power Act preempts such subsidies. Some parties also argued that by favoring within-state nuclear plant owners in wholesale power markets, the program violated the Constitution's dormant Commerce Clause. The U.S. Circuit appellate courts in both cases rejected the challenges and upheld the legality of the ZEC programs as designed.

2.3 The Research Question

Given these institutional details, the question examined in this analysis is how the implementation of ZECs in New York and then Illinois affected wholesale power market outcomes, retail prices, and the resulting concentrations of carbon dioxide and local air pollutants (namely SO_2, NO_2, and $PM_{2.5}$). While both states rely on nuclear generation as a baseload resource, the fuel mix in the two states differs in ways that may lead to the ZEC program having different effects.

Figure 1 displays annual generation shares by fuel source for the dominant fuel sources in each of the two states. Nuclear generation has a large share in both Illinois and New York; in particular, in Illinois over half of electricity generated in the state comes from nuclear plants. Other than nuclear's significance and the growth of "Other" reflecting wind (among other resources), the fuel source shares in the two states differ greatly. Illinois relies more heavily on coal, although coal shares have fallen significantly since 2014. Illinois has negligible hydroelectric generation, while New York's hydro generation share surpasses 20 percent. Natural gas generation also plays a substantially larger role in New York.

In both states the form of the ZEC requirement does not change relative prices or short-run marginal cost directly, but instead transfers rents from buyers to nuclear suppliers. Our theoretical predictions rely on the logic that a rent transfer to nuclear suppliers would enable them to make lower offers (as seen, for example, with the effect of production tax credits on the ability of wind suppliers to submit negative offers), increasing the likelihood of dispatch and thus increasing revenue. Making lower offers can shift nuclear's place in the supply curve and change the units that are dispatched, which for a given level of demand means that nuclear would substitute for generation from another fuel source. This logic suggests that we should observe an increase in nuclear generation in the ZEC states as compared to others.

With respect to wholesale market prices, the incentive for nuclear suppliers to make lower offers could lead to lower observed market-clearing prices. Another factor that could reduce price is the extent to which buyers have to pay for ZECs, which could lower their willingness to pay for the energy attributes in wholesale markets. However, the ZEC purchase requirement means that wholesale power buyers face an additional cost, which could increase market-clearing prices. With respect to retail prices, one important research question is the extent to which ZEC buyers have an incentive and ability to pass through that cost to consumers, which may be offset if wholesale market prices fall. The predicted effect on retail prices is an empirical question since these factors could move in either direction.

The predicted effect on carbon dioxide and air quality depends on how the generation mix changes as a result of the ZEC program. For example, if the substitution is between nuclear and coal generation as prior literature suggests, then increases in nuclear generation should lead emissions to fall (Severnini, 2017; Adler, Jha and Severnini, 2020). Again this is an empirical question, depending on the composition of the fuel mix and the specific manner in which the ZEC program affects that mix.

3 Empirical Strategy

3.1 Difference-in-Differences for ZEC Announcement and Implementation

To examine these outcomes more systematically, the next step is to understand how the ZEC program affected generation and emissions from both nuclear and non-nuclear sources in the two states. We first perform a standard difference-in-differences (DID) analysis of the change in our outcome of interest after the ZEC program was announced. The ZEC program is the treatment in the DID, and an observation in a month for a state participating in ZECs is a treated observation. We exclude neighboring states to both Illinois and New York that may have seen spillover effects from the implementation of these ZEC programs.[14] Illinois and New York are thus the treated states and all other non-neighboring states are untreated. Since the timing of ZEC program announcement

[14] The following states are excluded: Indiana, Iowa, Kentucky, Michigan, Missouri, and Wisconsin as neighbors of Illinois; and Connecticut, Massachusetts, New Jersey, Pennsylvania, and Vermont as neighbors of New York.

and implementation was different for Illinois and New York, if we ran a single DID with varying treatment windows we would encounter the issue highlighted in Goodman-Bacon (2018) whereby one treated observation would be part of the control group for another. To avoid this issue, we run our DID estimation separately for each treated state, excluding the other treated state from our analysis (i.e. separately for ZECs in Illinois against our control group and for ZECs in New York against our control).

We analyze the effects of both the announcement and the implementation of the ZEC program to account for any anticipatory behavior on the part of market participants. Generators knew the ZEC implementation date in advance, so their response to the program could have started prior to the implementation date. It seems less plausible that generators could anticipate the date the ZEC program was first proposed.

The regressions are of the general form:

$$\begin{aligned} Y_{smy} = &\alpha_0 + \beta_1 Post_{my} + \beta_2 Post * ZEC_{smy} \\ &+ \beta_3 ZEC\_start_{smy} + \beta_4 ZEC\_start * ZEC_{smy} \\ &+ \phi_{sy} + \gamma_{ty} + \epsilon_{smy} \end{aligned} \tag{1}$$

where our outcome variable Y is the monthly outcome variable of interest in state s, season t, month m, and year y, *ZEC* is a 1/0 indicator variable for whether a state participated in the ZEC program, *Post* is equal to one after the ZEC program was announced but before it was implemented and zero otherwise, and *ZEC_start* is equal to one after the ZEC program was implemented and zero otherwise. In Illinois *Post* reflects the 6-month period between announcement and implementation, while in New York it reflects the 8-month period between announcement and implementation. We include state-by-year fixed effects and also include different time trends across specifications; standard errors are clustered at the state-by-year level. Our coefficients of interest are β_2 and β_4, or the diff-in-diff coefficients, because the interaction captures the isolated effect of the announcement and the implementation on the dependent variable in the ZEC state.

3.2 Short-Term Impacts of the ZEC Program

To examine how the ZEC program effects propagated over time, we break down the effects of the ZEC program implementation into short-term windows. In other words, what was the effect of the ZEC program in the 1st 6 months versus the next 6 months, and after a year? We extend regression Equation (1) as follows:

$$\begin{aligned} Y_{smy} =& \alpha_0 + \beta_1 Post_{my} + \beta_2 Post * ZEC_{smy} + \beta_3 ZEC\_start6_{smy} \\ &+ \beta_4 ZEC\_start6 * ZEC_{smy} + \beta_5 ZEC\_start7\_12_{smy} \\ &+ \beta_6 ZEC\_start7\_12 * ZEC_{smy} + \beta_7 ZEC\_start13_{smy} \\ &+ \beta_8 ZEC\_start13 * ZEC_{smy} + \phi_{sy} + \gamma_{ty} + \epsilon_{smy} \end{aligned} \tag{2}$$

where ZEC_start6 is an indicator for the 1st 6 months of the ZEC program implementation, ZEC_start7_12 is an indicator for months 7-12, and $ZEC\_start13$ is equal to one starting a year after the ZEC program implementation date. In Equation (2), the coefficients β_4, β_6, and β_8 isolate the timing of the response to the ZEC program implementation. As before, we exclude neighboring states and the other state (e.g. exclude New York when analyzing Illinois, and vice-versa) in the estimation and cluster standard errors at the state-by-year level. The results of this short-run propagation analysis are reported in the Appendix.[15]

Our approach in analyzing the ZEC programs is focused on the short-term, intensive margin response to them. Our methodology is not well suited to analyzing the extensive margin response, such as from inducing entry or exit from other generating sources. Since the program was motivated in no small part by the desire to prevent existing near-zero emission nuclear power from shutting down, our analyses of the effects of the policy on the intensive margin are likely to underestimate the overall effect of the ZEC program in each state.

4 Data and Summary Statistics

4.1 Data

Our data on electric power generation come from EIA's Form 923 for 2000-2019. The data cover virtually all power plants in the U.S. and include total net generation, consumption, and fuel stock by plant. We aggregate these data by fuel type within a state for our main analyses.

Wholesale electricity price data come from regional transmission organizations (RTOs). We take the monthly average day-ahead locational marginal price (LMP)

[15]The Appendix, available separately, provides supporting figures, referred to here as Figure A.*, and tables, referred to here as Table B.*.

for reference nodes or state-level hubs in each RTO, where available. In addition to MISO, PJM, and NYISO, we collect data from ISO-New England (ISO-NE), Southwest Power Pool (SPP), and the Electric Reliability Council of Texas (ERCOT) to use in the control group in our analyses.[16] Monthly retail price data by state and consumption class (e.g. residential, commercial, and industrial) are provided by EIA's Form 861 for 2000-2019.

We leverage EPA's AirData monitoring network when we examine the environmental effects of the ZEC programs.[17] We use monthly data on ambient pollutant concentrations of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter ($PM_{2.5}$) from EPA's monitors across the U.S. Finally, we use data from EPA's Continuous Emissions Monitoring Systems (CEMS) database for the period 2010 – 2019 in our analysis of the impacts of the ZEC programs on emissions of carbon dioxide (CO_2).

4.2 Trends in Generation and LMP - Illinois

Figures 2 and 3 present average monthly net generation from power plants in Illinois from EIA's Form 923 database against the average monthly day-ahead LMP from MISO and PJM at the Illinois trading hub, respectively. The two dotted green lines represent the date when the ZECs were first proposed (12/1/2016) and the start date of the first delivery year of the ZECs program (6/1/2017), a 6-month interval. A notable change in generation evident in these figures is the decrease in coal generation starting in early 2016, well before the ZEC program announcement. Discerning evidence of a strong effect of the ZEC program from the data trends is difficult. We see some suggestive evidence of higher levels of fossil fuel generation and lower levels of nuclear power generation between the proposed and start dates of the ZEC program in 2017, compared to the same period in 2016. After the program begins, the LMP is generally higher in

[16] The day-ahead LMP data by RTO were downloaded from the following:
MISO: https://www.misoenergy.org/markets-and-operations/real-time--market-data/market-reports/#nt=\%2FMarketReportType\%3AHistorical\%20LMP\%2FMarketReportName\%3AHistorical\%20Annual\%20Day-Ahead\%20LMPs\%20(zip)&t=10&p=0&s=MarketReportPublished&sd=desc;
PJM: http://dataminer2.pjm.com/feed/da_hrl_lmps;
NYISO: http://mis.nyiso.com/public/P-28list.htm;
ISO-NE www.iso-ne.com/isoexpress/web/reports/pricing/-/tree/monthly-lmp-indices;
SPP: https://marketplace.spp.org/pages/da-lmp-by-bus#;
ERCOT: http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13060&reportTitle=Historical\%20DAM\%20Load\%20Zone\%20and\%20Hub\%20Prices.

[17] Data downloaded from https://aqs.epa.gov/aqsweb/airdata/download_files.html.

the first year after the program than in the pre-period, while the net generation from fossil fuel plants appears slightly lower. There appears to be little change to nuclear generation after the program begins. Wind generation exhibits the same seasonality in the first years before and after the program, but it drops off significantly in 2019 (an approximately 40 percent reduction from 2018 to 2019). These changes coincide with lower overall levels of generation in the interval between ZEC program announcement and implementation.

To get a better sense of longer-term trends in generation and electricity prices, we can look back further to 2000. These extended versions of Figures 2 and 3 can be seen in Figures A.1 and A.2, respectively. Due to limitations in the LMP datasets from PJM and MISO we do not have full price data over the longer period. Nonetheless, in Illinois prices are generally below their pre-wind levels both before and after the introduction of the ZEC program. These trends take place in a context with additions to and retirements from the generation fleet; Table B.1 reports additions and retirements by fuel type and capacity for Illinois, New York, and non-neighboring control states.

4.3 Trends in Generation and LMP – New York

We present the same data for the state of New York in Figure 4 and Figure A.3, respectively. New York's ZEC program was announced on August 1, 2016, and implemented on April 1, 2017 (an 8-month interval). Compared to the same period in the year prior, generation from nuclear power experienced a roughly 4.5 percent reduction between the proposed and announced date of the ZEC program (e.g. August 2015 – April 2016 vs. August 2016 – April 2017). That reduction exceeded the 3.4 percent reduction in total demand. This 4.5 percent decrease for nuclear was roughly on par with decreases seen for fossil fuel generation. In contrast with Illinois, New York has substantial generation from hydroelectric power; over this same time period, hydro generation saw a relative increase, as it only decreased by 0.7 percent. Additionally, wind generation increased over this period by nearly 5 percent.

In terms of energy prices, day-ahead LMPs in the NYISO market were fairly low leading up to the ZEC program announcement date. After the program was proposed and before it was implemented, average LMPs increased by about 21 percent compared to the same period one year prior. After ZEC program implementation, we observe an overall increase in average LMPs again of over 20 percent, driven largely by a single price spike in January 2018 of \$58.54/MWh. In Figure A.3 we see that prices were on a downward trend from around mid-2008 to the ZEC proposal date in August 2016, apparently driven in large part from the switch from coal to cheap natural gas. While the ZEC program announcement did increase energy prices, energy prices overall were still on par with those in NY from almost 20 years earlier (in nominal terms).

5 Results

We first analyze the effects of the ZEC program on both nuclear and other sources of generation in Section 5.1. Results for the impacts on wholesale and retail prices are presented in Sections 5.2 and 5.3, respectively. Finally, changes to ambient air quality and carbon dioxide emissions are discussed in Section 5.4.[18]

5.1 Generation

We begin by examining the effect of the ZEC program on generation, where our outcome variable is monthly net generation from a given fuel source. We perform this analysis separately for each dominant fuel type in each respective state and include a control for total monthly state load. When we examine generation from non-nuclear fuel sources, we also include a control for monthly nuclear generation.

Focusing first on Illinois, we see in Table 1 that the ZEC program announcement led to an increase in nuclear power generation of just over 500 GWh per month, and the program implementation increased nuclear generation by nearly 980 GWh per month after the ZEC program started, relative to non-participating states (and excluding New York). These effects are robust to different specifications of time fixed effects, as seen in columns (2) - (4) in Table B.2 in the Appendix. The magnitude of this increase is consistent with the relatively large regional role of nuclear in the generation portfolio, particularly in comparison to control states with substantially less nuclear capacity.

We examine the impact of the ZEC program on non-hydro renewable generating sources in Table 1. The primary response from our results appears to be an increase in renewable generation (280 GWh) after the announcement of the program, with no significant response at the 5% level after ZEC implementation. This increase may be

[18]We present figures with the raw monthly average trends for our control group and the state of interest for each set of results in Section A.2 of the Appendix. While the figures just present the raw trends in outcomes without any controls, the trends are not parallel in all cases which suggest that our estimates in these specific cases imply correlation instead of causation (noted as an association in the text).

offset by a decrease in generation from natural gas (roughly 420 GWh) associated with the ZEC announcement, reported in Table B.4.[19]

By comparison, in New York the announcement of the ZEC program increased nuclear generation by about 320 GWh, with average monthly nuclear generation increasing by roughly double at 640 GWh after the ZEC program began (see Table 2). These increases appear to be offset in large part by decreases in coal generation of around 340 and 500 GWh after the announcement and implementation of the ZEC program, respectively. We see some suggestive evidence of an increase in generation from natural gas (300 GWh); however, we do not have parallel trends for natural gas or the remaining generation sources shown in columns (3) - (5) of Table B.5 and thus cannot claim causality.

The generation results show anticipatory adjustments to the new ZEC program by nuclear generators in both Illinois and New York. The magnitude of the program's effects on nuclear generation was also larger in Illinois than New York. In Illinois the announcement of the ZEC program contributed to increases in wind generation, with no conclusive impact on fossil fuel or renewable generation after the program began. In New York, the ZEC program announcement and implementation led to reduced coal-fired generation and increased nuclear generation, with no conclusive evidence of impacts on natural gas, fuel oil, or renewable generation.[20]

5.2 Wholesale Prices

We can also look at the short-term impacts of the ZEC programs on wholesale prices. Data on wholesale prices come from day-ahead locational marginal price (LMP) data for major hubs in NYISO, MISO, and PJM, as well as ISO-NE, SPP, and ERCOT. As before, we exclude hub prices in neighboring states that are likely to see spillover effects from the ZEC subsidy. We also limit our analyses of the price effects to 2013-2019, or the period when price data are available for all 3 markets.

Since Illinois participates in both the PJM and MISO markets, we separately estimate the effects of the ZECs on wholesale prices in PJM and MISO in columns (1) and (2) of Table 3. In both markets, we find a decrease in wholesale prices after the ZEC program is announced - \$4.03/MWh in PJM and \$3.85/MWh in MISO - and a

[19] We cannot claim causation here due to a lack of parallel trends; see Figure A.4.

[20] Figure A.13 presents estimated monthly nuclear capacity factors, with no discernable difference at the monthly level before and after ZEC announcement.

similar reduction after the program started (\$4.77/MWh and \$3.57/MWh in PJM and MISO, respectively). On average, these changes after the announcement correspond to a roughly 12.6% and 12.7% decrease in wholesale prices in the respective markets. When we further decompose the ZEC program into 6-month windows in Table B.14, we see a larger decrease in prices in the latter half of the first year in both MISO and PJM relative to the first 6 months, and no significant changes after one year.

The observed trends in PJM and MISO in the first year after ZEC implementation are consistent with nuclear generators offering in at lower prices due to the presence of the ZEC subsidy, displacing higher cost generation at the margin and lowering average wholesale prices. We find evidence of a similar ZEC effect on wholesale prices in New York in Table 4.

In New York, the implementation of the ZEC program led to a significant decrease in the wholesale price of roughly \$3.2/MWh. This decrease translates to a 9.3% reduction in average prices in NYISO, all else equal. There was no change in wholesale prices from the program announcement, and the further breakdown by 6-month bins in Table B.15 shows that the majority of the price difference is driven by the first 6 months after the ZECs were put in place. Recall that in contrast with Illinois, we found evidence of a significant reduction in coal generation offsetting the increase in lower cost nuclear generation (particularly in the 1st 6 months, see Table B.13).

5.3 Retail Prices

Next we examine whether the ZEC program led to changes in the electricity prices consumers pay for power. The three main classes of consumers are residential, commercial, and industrial; we estimate the effects of the program separately on each class and on total average retail electricity prices. As shown in Table 5, the announcement of the ZEC program in Illinois led to a \$0.30/MWh *decrease* in residential prices and a larger \$0.78/MWh decrease in prices once the ZEC program began.[21] In this case the offsetting effects of the ZEC program to reduce wholesale prices (as seen in Sections 5.1 and 5.2) led overall to a slight reduction in residential prices. This result is consistent with our findings of a statistically and economically significant decrease in wholesale prices in Illinois in Table 3, providing evidence of a pass-through of a portion of these reduced costs from the electric utilities to consumers. Such pass-through has

[21] Results for other consumer classes in Table B.6 suggest similar price patterns, however we cannot claim causality for non-residential consumers (see Figure A.8).

always been a component of the policy argument for moving from vertically-integrated, regulated utilities to wholesale and retail market competition.

The effects we find in Illinois stand in stark contrast to our findings for New York in Table 6. Across all sectors, we see a significant increase in retail electricity prices after the announcement and start of the ZEC program. These price increases are largest for the commercial and residential sectors. There appears to be some seasonality in the price effect; when we estimate Equation (2) in Table B.17, the effect is over a \$1/MWh increase in prices in the first 6 months and one year after after the ZEC program began, with a relatively smaller increase in prices in the latter half of the first year. Although wholesale prices decreased in New York (see Section 5.2), in contrast with Illinois we see a rise in retail prices to cover the costs of the ZEC subsidy.

In short, we find evidence of a small residential price decrease in the short-term due to the ZEC program in Illinois, suggestive of a pass-through of the reduced wholesale cost of electric generation. In contrast, in New York we find price increases due to the ZEC program in the commercial and residential sectors. This result suggests little or no pass-through of the reduced wholesale costs of power while passing through the higher cost of the subsidy to retail consumers in New York.

5.4 Air Quality

5.4.1 Ambient Air Quality

One motivation for implementing ZECs was providing a payment to nuclear plants to recognize their benefits as a near-zero-emission source of electric power. We estimate modified versions of Equations (1) and (2) to analyze the state-level impacts of the ZECs program on ambient air concentrations of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter ($PM_{2.5}$). Recall that our data are not on emissions but on local air pollutant concentrations measured at in-state monitors, so we are measuring the change in air pollution levels experienced by the states participating in the ZEC program.[22] Thus, our estimates provide a measure of the relative benefit (or damage) to air quality in Illinois or New York due to the ZEC program.

In Illinois, we see in Table 7 that ambient SO_2 concentrations decreased by roughly 2 parts per billion (ppb) on average after both the announcement and the implementation

[22] In contrast with our approach for generation, if for example the ZEC program caused neighboring, out-of-state coal generators that are upwind to generate more, pollution from those stacks that was transported into a ZEC state would be captured in our measures of air quality in the ZEC state.

of the ZECs program. We see a similar decrease of roughly 2ppb for NO_2 after the ZEC program began. Our results for $PM_{2.5}$ in Illinois are inconclusive, likely due to data limitations.[23] In contrast, we find a significant 1 microgram/cubic meter ($\mu g/m^3$)) decrease in $PM_{2.5}$ in New York due to the ZECs program, and a similar but smaller decrease in SO_2 concentrations of about 0.75 ppb (see Table 8).

When we decompose the effect further with our modified version of Equation (2), the impact on SO_2 shown in Table B.18 is quite stable, while the effects we saw in Table 7 for NO_2 accelerate in the latter half of the year and beyond. New York exhibits less variation, with both SO_2 and $PM_{2.5}$ concentrations decreasing by roughly 1 unit (ppb or $\mu g/m^3$, respectively) in all periods after the ZECs were put in place.

The similarities in the observed effects on ambient air quality in New York and Illinois can be explained through the general generation responses seen in each state. As seen in Table B.5, the increased nuclear generation from ZECs in New York was offset by a decrease in generation from coal, which would tend to improve air quality. And while our results for fossil fuel generation in Illinois are not causal (see Figure A.4), we do find evidence that the ZECs program was associated with a reduction in natural gas generation and caused an increase in renewable generation (Table B.4). The air quality improvements observed in both states also suggest no large increases in pollution from out-of-state generators being transported into the program areas.

5.4.2 CO_2 Emissions

A primary objective of the zero emission credit programs was to encourage a decrease or at a minimum prevent an increase in CO_2 emissions. As we did for ambient air quality above, we estimate modified versions of Equations (1) and (2) to analyze the state-level impacts of the ZECs program on emissions of carbon dioxide (CO_2). We now focus on the source of these state-level emissions, as whether or not the pollutant is transported across state lines does not affect its impact on climate. Due to a decrease in Illinois' CO_2 emissions in the year or so prior to the ZEC announcement (see Figure A.12), we focus our analysis on New York.

The estimation results can be seen in Table 9. Relative to the states in our control group, we see a significant decrease in monthly CO_2 emissions after both the announcement and implementation of the ZECs program in New York. This result is consistent

[23] Data on $PM_{2.5}$ concentrations in Illinois are missing in our dataset for several years in the pre-period (June 2011 - 2014), as shown in Figure A.10. Nonetheless, results for $PM_{2.5}$ can be found in Table B.8.

with our previous findings of a decrease in coal generation due to the ZECs program and the associated improvements in local air quality for New York discussed above. Thus, we find evidence that the ZEC policy led to decreased greenhouse gas emissions in the short-term in New York.

6 Conclusion

New York and Illinois implemented a new regulatory instrument, Zero Emission Credits, in an attempt to address the financial challenges now facing nuclear power plants in their wholesale power markets. Our analysis suggests that the ZEC program has affected market outcomes and air quality differently in Illinois and New York, reflecting specific aspects of each state's institutional context and resource mix.

In Illinois the ZEC program increased nuclear and wind generation at both program announcement and implementation, and was associated with a decrease in natural gas generation. In New York the ZEC program increased nuclear generation and reduced coal-fired generation at both program announcement and implementation. It also was associated with an increase in hydro generation. These changes in the generation mix led to a short-term improvement in air quality in both states and a decrease in greenhouse gas emissions in New York. Wholesale prices generally fell, but the increased dispatch of nuclear plants may yield enough revenue associated with their near-zero-emission attributes to enable them to continue operations. Retail prices decreased in Illinois and increased in New York due to the ZECs program, suggesting varying approaches to the pass-through of additional costs or savings in each state.

These results can inform policy makers as they assess the short-term impacts of the ZEC program. Our study provides a useful reference for other states that have since implemented or are considering implementing ZECs, and it also highlights the importance of considering the existing resource mix in that state or region.

Future work can extend our findings to examine the impacts of ZEC programs introduced more recently in other states, such as Ohio and New Jersey. Additionally, this paper focuses on the short-term effects of the ZEC program; longer-run effects, both on the intensive and extensive margin (such as inducing entry or exit), are of critical importance for a complete evaluation of these subsidies.

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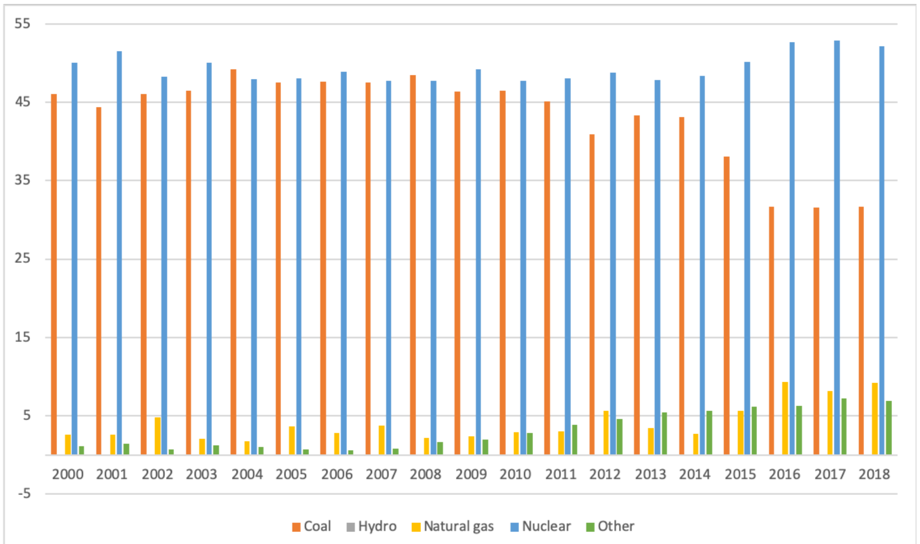
Figures and Tables

(A) Illinois



(B) New York

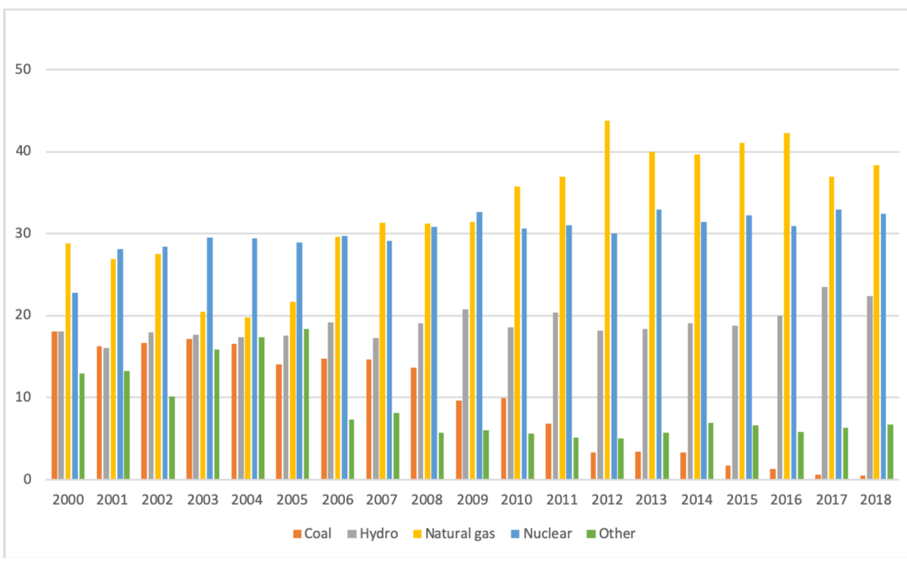


Figure 1: Generation (MWh) Shares by Fuel Source, 2000-2018

Notes: Data on generation in megawatt hours from EIA Detailed State Data, March 2020. `https://www.eia.gov/electricity/data/state/`

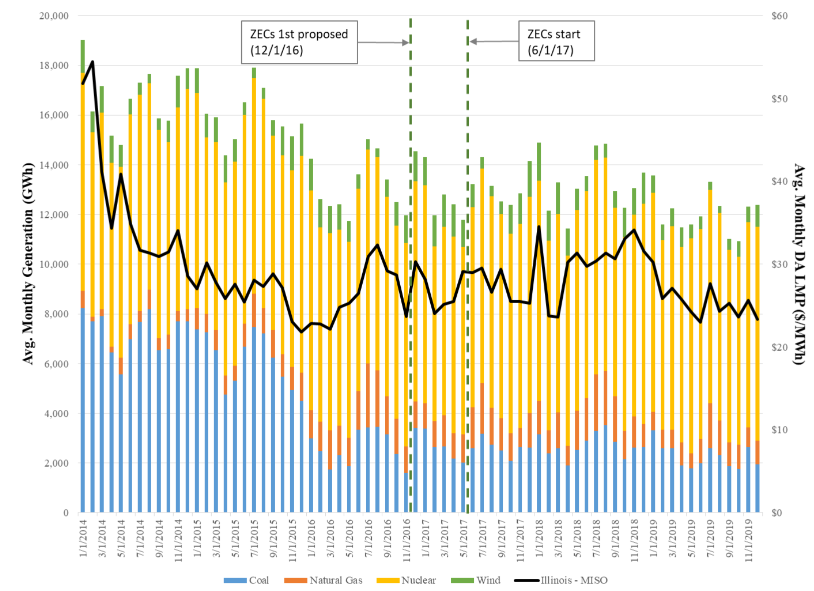


Figure 2: Avg. Generation and MISO DA LMP (2014-2019)

Notes: Total generation by fuel type from EIA Form 923 for power plants in Illinois. MISO average day-ahead monthly LMP for the Illinois Hub.

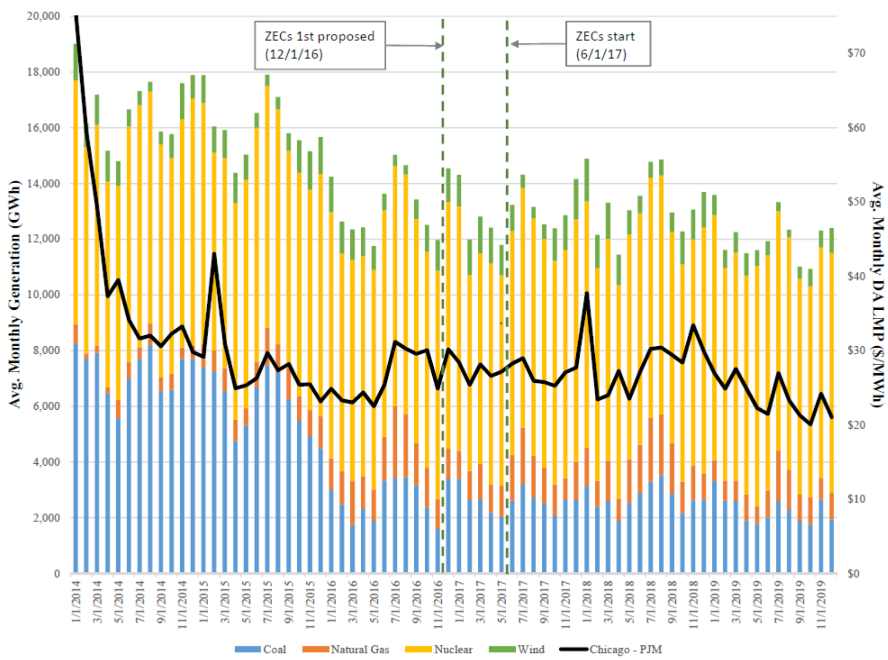


Figure 3: Avg. Generation and PJM DA LMP (2014-2019)

Notes: Total generation by fuel type from EIA Form 923 for power plants in Illinois. PJM average day-ahead monthly LMP for the Chicago Hub.

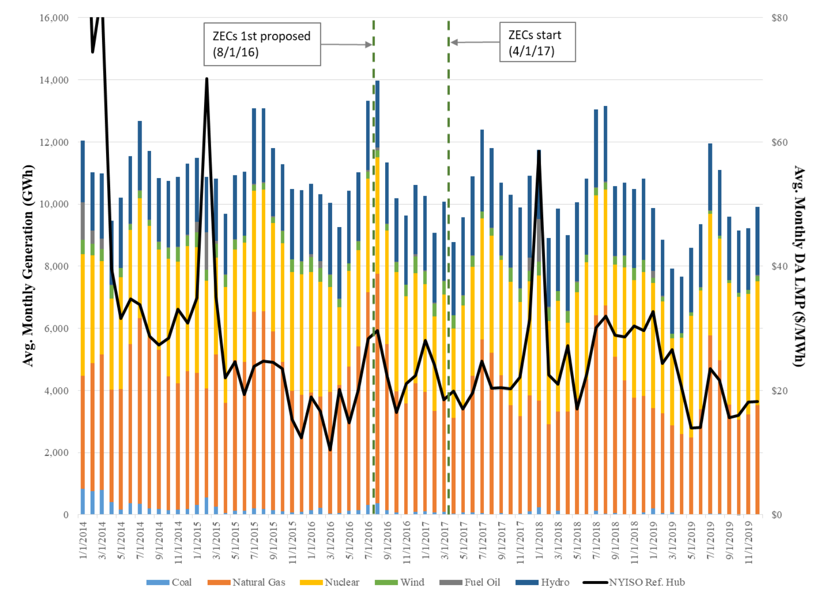


Figure 4: Avg. Generation and NYISO DA LMP (2014-2019)

Notes: Total generation by fuel type from EIA Form 923 for power plants in Illinois. NYISO average day-ahead monthly LMP for the NYISO Reference Hub.

Table 1: Impacts on Generation (Illinois, Pre- and Post- Implementation)

	(1) Nuclear	(2) Non-Hydro Renewable
Nuclear Generation		-0.01
		(0.01)
Total Load	0.07***	0.00
	(0.01)	(0.01)
6-mo. Post	53.78	98.58***
	(43.56)	(27.27)
ZEC Start	111.80**	215.65***
	(49.95)	(38.24)
6-mo. Post x Illinois	515.34***	278.03***
	(35.49)	(37.67)
ZEC Start x Illinois	983.52***	-41.37
	(44.96)	(52.71)
Constant	802.84***	310.67***
	(40.44)	(41.31)
R-squared	0.98	0.96
N	8,880	8,880
State-by-Year FE	Yes	Yes
Season-by-Year FE	Yes	Yes

Estimation of Equation (1) where the outcome variable is monthly nuclear generation by state in GWh from EIA Form 923 for 2000 - 2019. New York and neighboring states to New York and Illinois are excluded from this analysis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 2: Impacts on Generation (New York, Pre- and Post- Implementation)

	(1) Nuclear	(2) Coal
Nuclear Generation		-0.17***
		(0.03)
Total Load	0.07***	0.27***
	(0.01)	(0.02)
8-mo. Post	17.06	187.59***
	(24.14)	(64.26)
ZEC Start	-16.21	132.87*
	(43.46)	(72.80)
8-mo. Post x New York	324.57***	-345.76***
	(31.06)	(79.45)
ZEC Start x New York	642.81***	-497.63***
	(46.37)	(88.87)
Constant	731.71***	944.00***
	(37.51)	(83.32)
R-squared	0.97	0.98
N	8,880	8,880
State-by-Year FE	Yes	Yes
Season-by-Year FE	Yes	Yes

Estimation of Equation (1) where the outcome variable is monthly nuclear generation by state in GWh from EIA Form 923 for 2000 - 2019. Illinois and neighboring states to New York and Illinois are excluded from this analysis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 3: Impacts on LMP (Illinois)

	(1) Chicago Hub - PJM	(2) Illinois Hub - MISO
6-mo. Post	8.91***	8.97***
	(1.27)	(1.28)
ZEC Start	16.10***	16.02***
	(3.11)	(3.12)
6-mo. Post x Illinois	-4.03**	-3.85**
	(1.80)	(1.80)
ZEC Start x Illinois	-4.77**	-3.57*
	(1.85)	(1.85)
Constant	29.92***	29.79***
	(1.29)	(1.30)
R-squared	0.39	0.39
N	1,642	1,642
Hub-by-Year FE	Yes	Yes
Season-by-Year FE	Yes	Yes

Estimation of Equation (1) where the outcome variable is the monthly average hub LMP. Monthly average LMP data from 2013 - 2019 for reference nodes in NYISO, SPP, ERCOT, ISO-NE, MISO, and PJM. Hub prices for New York and neighboring states to both Illinois and New York are excluded from this analysis. Standard errors clustered by hub-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 4: Impacts on LMP (New York)

	(1) NYISO Reference Hub
8-mo. Post	6.15***
	(0.79)
ZEC Start	9.64***
	(1.32)
8-mo. Post x New York	-0.69
	(0.43)
ZEC Start x New York	-3.24***
	(0.65)
Constant	32.79***
	(0.92)
R-squared	0.40
N	1,642
Hub-by-Year FE	Yes
Season-by-Year FE	Yes

Estimation of Equation (1) where the outcome variable is the monthly average hub LMP. Monthly average LMP data from 2013 - 2019 for reference nodes in NYISO, SPP, ERCOT, ISO-NE, MISO, and PJM. Hub prices for Illinois and neighboring states to both Illinois and New York are excluded from this analysis. Standard errors clustered by hub-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 5: Impacts on Retail Prices (Illinois, Pre- and Post- Implementation)

	(1) Residential
Sales (MWh)	-0.00***
	(0.00)
6-mo. Post	0.17***
	(0.06)
ZEC Start	0.22**
	(0.10)
6-mo. Post x Illinois	-0.30***
	(0.08)
ZEC Start x Illinois	-0.78***
	(0.10)
Constant	9.93***
	(0.03)
R-squared	0.97
N	8,880
State-by-Year FE	Yes
Season-by-Year FE	Yes

Estimation of Equation (1) where the outcome variable is the monthly average retail price. Data from EIA's Form 861 for 2000 - 2019 on monthly average retail prices by state. New York and neighboring states to both Illinois and New York are excluded from this analysisis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 6: Impacts on Retail Prices (New York, Pre- and Post- Implementation)

	(1) Residential	(2) Commercial	(3) Total
Sales (MWh)	-0.00*	0.00***	0.00***
	(0.00)	(0.00)	(0.00)
8-mo. Post	0.11***	-0.03	0.06
	(0.04)	(0.04)	(0.04)
ZEC Start	0.23***	-0.05	0.01
	(0.09)	(0.06)	(0.06)
8-mo. Post x New York	0.43***	0.53***	0.48***
	(0.04)	(0.05)	(0.04)
ZEC Start x New York	0.95***	1.46***	1.12***
	(0.10)	(0.09)	(0.07)
Constant	10.07***	8.19***	7.94***
	(0.03)	(0.13)	(0.08)
R-squared	0.97	0.96	0.97
N	8,880	8,867	8,880
State-by-Year FE	Yes	Yes	Yes
Season-by-Year FE	Yes	Yes	Yes

Estimation of Equation (1) where the outcome variable is the monthly average retail price. Data from EIA's Form 861 for 2000 - 2019 on monthly average retail prices by state. Illinois and neighboring states to both Illinois and New York are excluded from this analysisis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 7: Impacts on Air Quality (Illinois, Pre- and Post- Implementation)

	(1) SO2	(2) NO2
6-mo. Post	0.11	-1.13**
	(0.19)	(0.48)
ZEC Start	0.20	-0.62
	(0.42)	(0.83)
6-mo. Post x Illinois	-1.92***	-2.83***
	(0.19)	(0.69)
ZEC Start x Illinois	-1.95***	-2.30***
	(0.29)	(0.75)
Constant	7.16***	23.23***
	(0.09)	(0.15)
R-squared	0.87	0.85
N	8,733	8,072
State-by-Year FE	Yes	Yes
Season-by-Year FE	Yes	Yes

Estimation of Equation (1) where the outcome variable is monthly ambient concentrations of a local air pollutant by state from EPA's AQS Database for 2000 - 2019. New York and neighboring states to and neighboring states to New York and Illinois are excluded from this analysis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 8: Impacts on Air Quality (New York, Pre- and Post- Implementation)

	(1) SO2	(2) PM2.5
8-mo. Post	0.01	-0.08
	(0.11)	(0.29)
ZEC Start	-0.11	0.37
	(0.25)	(0.45)
8-mo. Post x New York	-0.36***	-0.96***
	(0.11)	(0.26)
ZEC Start x New York	-0.76***	-1.01**
	(0.27)	(0.39)
Constant	7.14***	11.61***
	(0.08)	(0.11)
R-squared	0.87	0.51
N	8,733	8,713
State-by-Year FE	Yes	Yes
Season-by-Year FE	Yes	Yes

Estimation of Equation (1) where the outcome variable is monthly ambient concentrations of a local air pollutant by state from EPA's AQS Database for 2000 - 2019. Illinois and neighboring states to and neighboring states to New York and Illinois are excluded from this analysis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.

Table 9: Impacts on CO2 Emissions (New York, Pre- and Post- Implementation)

	(1) CO2
8-mo. Post	326.86***
	(79.14)
ZEC Start	503.65***
	(126.95)
8-mo. Post x New York	-211.70**
	(92.32)
ZEC Start x New York	-401.10**
	(177.42)
Constant	3063.44***
	(49.04)
R-squared	0.96
N	4,440
State-by-Year FE	Yes
Season-by-Year FE	Yes

Estimation of Equation (1) where the outcome variable is monthly emissions ('000 short tons) of CO_2 by state from EPA's CEMS Database for 2010 - 2019. Illinois and neighboring states to New York and Illinois are excluded from this analysis. Standard errors clustered by state-by-year in parentheses. ***, **, and * represent significance at 1%, 5%, and 10%, respectively.