Nuclear Retirement Effects on CO_2 Emissions

Preserving a Critical Clean Resource

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Executive Summary

In recent years, wholesale electricity prices and CO_2 emissions from generation have both declined, primarily due to lower natural gas prices (which has led to significant coal-to-gas switching), along with negligible demand growth and substantial amounts of new renewable generation coming online. Lower wholesale power prices and reduced CO_2 emissions are generally positive developments for consumers and the environment; however, there is a tension between these effects. Persistently low power prices can threaten the economic viability of existing nuclear generators, which currently provide the majority of carbon-free power in the United States.

The potential vulnerability of some nuclear power plants to premature retirement creates a major threat to the attainment of CO_2 reduction goals. Although the Environmental Protection Agency's (EPA) Clean Power Plan has been stayed pending legal challenges, and may be rescinded by the new administration, any carbon abatement program will be made more difficult by a loss of nuclear generation. This analysis examines the aggregate and regional carbon emission impacts that premature nuclear retirements might cause, and evaluates the implications of such retirements for the ability to achieve carbon reductions in the power sector. In this report, we find that:

- Some nuclear units do not earn sufficient revenue to cover going-forward costs and thus are vulnerable to premature economic retirement under current market conditions. The revenue shortfalls experienced by the most vulnerable plants—typically the small, single-unit plants operating in markets with particularly low energy prices—can be as high as about $20/MWh, though most experience smaller shortfalls.
- If a nuclear unit retires prematurely, coal and gas generation will increase to replace the lost nuclear output in the near term, causing CO_2 emissions to rise. Not all nuclear retirements would have the same environmental impacts, however; the likely increase in near-term CO_2 emissions from a given nuclear retirement depends significantly on the region in which it occurs. A 1,000 megawatt (MW) nuclear retirement would cause increased CO_2 emissions in the range of 4.1 to 6.7 million tons per year, or 0.52-0.84 tons per MWh.

- The increased level of CO_2 emissions arising from a premature nuclear retirement is not confined to the state in which the unit resides. In fact, in most cases the majority of this increase will occur outside the state, and a significant amount of the emissions increase will occur in states beyond those adjacent to the state experiencing the retirement. The geographic dispersion of emission effects through regional electricity markets may pose a challenge to state-level climate policies, including any national policies that create state-level compliance requirements.

- Premature nuclear retirements will make any climate policy measures more costly and/or less effective. Assuming a revenue deficit of $10/MWh for a vulnerable nuclear plant, the cost of avoiding CO_2 emissions by retaining nuclear capacity ranges between $12 and $20 per ton of CO_2, depending on regional emissions rates. This cost compares favorably with other carbon abatement options, the estimated social cost of carbon, and the cost of state policies designed to reduce CO_2 emissions from the power sector. For example, New York's recent Clean Energy Standard program provides its upstate nuclear plants, which are challenged by high operating costs and low power prices, with Zero Emission Credits initially worth $17.48/MWh. This will save the Fitzpatrick plant from an announced premature shutdown in January 2017, and prevent a similar fate for the Ginna and Nine Mile Point plants.

- Since CO_2 emissions persist for many years in the atmosphere, near-term emission reductions are more helpful for climate protection than later ones. Thus, preserving existing nuclear plants will improve the effectiveness of any climate policy approach, by holding down cumulative emissions, and/or reducing the cost of achieving any particular cumulative emissions level. Retaining existing nuclear assets in the near-term will also maintain option value for achieving future CO_2 reductions, if the longer-term transition to alternative carbon-free power sources proves to be more difficult or time-consuming than currently anticipated.

- Although beyond the scope of this paper, nuclear reactors also have a significant effect on other pollutants emitted by fossil generators. In a separate analysis, The Brattle Group found that nuclear power avoids air emissions of over one million tons of sulfur dioxide and 650,000 tons of nitrogen oxides each year, as well as significant particulate emissions.[1] The estimated total value to society of avoiding these criteria pollutants is over $9 billion annually.

These findings demonstrate that the retention of existing nuclear generating plants, even at a modest premium, represents a cost-effective method to avoid CO_2 emissions and enable compliance with any future climate policy, whether it is the Clean Power Plan or an alternative, at reasonable cost. Sustaining nuclear viability in the interim will reduce near-term emissions, and is a reasonable and cost-effective insurance policy in the longer term.

I. Introduction

In August 2015, the EPA finalized the Clean Power Plan (CPP), a rule under Section 111(d) of the Clean Air Act to limit CO_2 emissions from existing fossil electricity generation sources through 2030. In February 2016, the CPP was stayed pending legal challenge, which may result in overturning the rule or remanding it to the EPA. Now with the change of administration, it may be rescinded. Nonetheless, climate change continues to be a pressing concern, and future U.S. climate policy at state and national levels is likely to continue to focus on electricity sector CO_2 emissions. In this context, existing nuclear plants play a crucial role in limiting CO_2 emissions, which would be threatened if economic pressures led to premature nuclear retirements. In this analysis, we examine the aggregate and regional carbon emissions impact of possible nuclear closures, and evaluate the implications of such retirements for compliance with any state or federal policy designed to achieve meaningful reductions in carbon emissions from the electric sector. Our analysis does not assess the vulnerability of specific nuclear units or estimate the cost of providing sufficient support to keep them viable. Instead, we examine a representative range of CO_2 emission benefits from providing such support as may be needed to forestall premature nuclear retirements. Given the goals and likely costs of future climate policy, we find that sustaining nuclear viability in the near term provides a cost-effective means of achieving emission reduction objectives, including through state-level policies such as expanding renewable portfolio standards. In 2015, nuclear energy provided 20% of all U.S. net generation; this is nearly 60% of the carbon-free electricity generated in the U.S., considerably more power than is provided by solar, wind, and hydroelectricity combined. These shares are reflected in Table 1.

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1 *The Nuclear Industry's Contribution to the U.S. Economy*, The Brattle Group, July 2015.

Table 1: U.S. Generation Mix (2015)

Generation Type	Share of Generation
Coal	34%
Natural Gas	32%
Nuclear	20%
Hydropower	6%
Other Renewable	7%
Wind	4.9%
Biomass	0.8%
Geothermal	0.4%
Solar	0.7%
Petroleum	0.7%
Other Gases	<1%

Source: EIA Monthly Energy Review, July 2016, Table 7.2b

Due to recent low wholesale power price conditions in many regions, and the relatively high fixed operating costs at many nuclear stations, some nuclear units may be vulnerable to premature economic shutdown in the near future. In fact, three nuclear units, Kewaunee in Wisconsin, Vermont Yankee in Vermont, and Fort Calhoun in Nebraska have recently retired. Three more units—Pilgrim, Oyster Creek, and Palisades, representing over two GW of capacity—have announced that they will retire over the next few years, all due, at least in part, to poor operating economics.[2] Public statements from owners of other nuclear plants indicate that some fear similar implications for portions of their nuclear fleets. The closures of Kewaunee (566 MW) and Vermont Yankee (604 MW)—both relatively small units, and together representing only about one% of the total generating capacity of the U.S. nuclear fleet—have already had significant environmental consequences, increasing CO_2 emissions by 6.4 million tons per year. This is the equivalent of adding about 1.2 million cars to the roads.[3]

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2 The Fitzpatrick nuclear unit (917 MW) in New York was also announced by Entergy to retire in 2017, but will now continue to operate as a result of the recent acquisition of the plant by Exelon, facilitated by additional revenues from Zero Emission Credits (ZECs) under New York's Clean Energy Standard. Similarly, recent action by the Illinois legislature will ensure the continued operation of the Clinton and Quad Cities plants.

3 According to the EPA, a typical passenger vehicle emits about 4.7 metric tons (5.18 short tons) of CO_2 per year. See Greenhouse Gas Emissions from a Typical Passenger Vehicle, EPA, May 2014. Throughout this paper, references to tons indicate short tons.

II. The Economics of Potential Premature Nuclear Retirement

A number of factors have combined to threaten the economic viability of some existing nuclear plants, particularly "merchant" plants that depend on revenues from wholesale energy and capacity markets to cover their operating costs, and are not owned by load-serving entities who recover investment and operating costs through regulated retail rates. Perhaps the primary factor is low natural gas prices over the past several years, which have put substantial downward pressure on wholesale power prices.

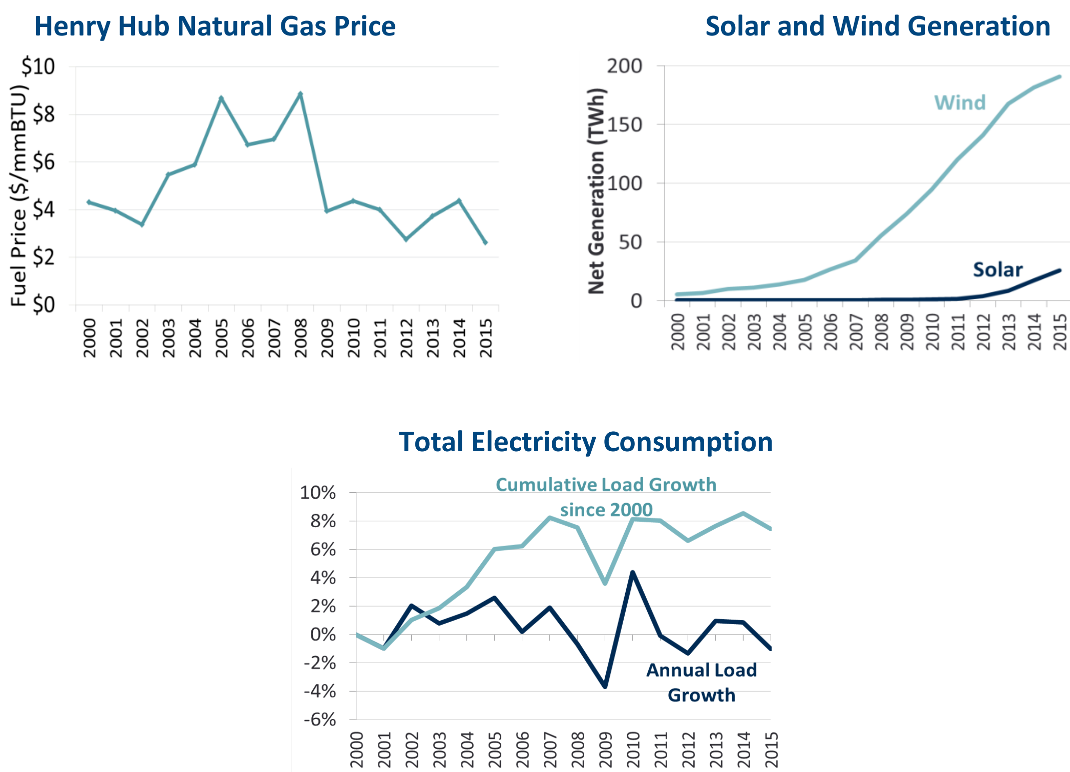
B. WHOLESALE MARKET REVENUES

In organized wholesale energy markets administered by independent system operators (ISOs) or regional transmission organizations (RTOs), the wholesale price of energy is set by the interaction of supply and demand, which are driven primarily by external market drivers (such as the cost of natural gas fuel). But a variety of policies also affects both supply and demand in ways that can affect prices. Even in areas dominated by regulated utilities, such as the Southeast and Western U.S., wholesale power markets exist and are affected by fuel costs and other market drivers. Because natural gas is frequently the "marginal" fuel in power markets, it has an outsized effect on wholesale energy prices. The advent of shale gas at the end of the last decade is probably the biggest single factor driving lower prices for wholesale power. Current natural gas prices are less than half the levels that prevailed before the shale gas revolution, and wholesale electricity prices have fallen by a substantial amount over the same period. For example, annual average all-hours energy prices in 2015 were $36/MWh at the PJM Western Hub, $29/MWh at MISO Indiana Hub, and $20/MWh at SPP North Hub.

But low gas prices are not the only factor depressing market prices for power. Significant penetration of renewables in response to state-level renewable portfolio standards (and contracting or tax incentives) has helped to push down energy prices in some regions. More broadly, many regions are experiencing low load growth, due to the success of efficiency and demand-side management programs, and a slow recovery from the recession of 2008-2009. Slow growth tends to create slack in the supply-demand balance, which reduces both capacity and energy prices and the value of generation plants generally. And in some areas with plenty of low-cost supply, transmission constraints can make it difficult to move power to load centers, depressing prices locally.

Low power prices, while welcome for consumers in the short run, reduce the revenues that merchant nuclear plants can earn from selling their output.[4] Figure 1 below summarizes gas prices, renewable additions, and load growth over the past decade and a half, illustrating the fall in gas prices, the rise in renewable generation, and flat overall load that are combining to present an economic challenge to some nuclear plants.

Figure 1: Factors Affecting U.S. Power Prices Since 2000



Sources: Henry Hub natural gas price from EIA, in nominal $. Solar and wind generation from "EIA Monthly Energy Review", July 2016. Electricity consumption from "EIA Short-term Energy Outlook," August 2016.

C. Nuclear Operating and Maintenance Cost

On the cost side, nuclear plants have very low fuel and variable costs, but relatively high fixed operating and maintenance costs, as well as repair and replacement capital expenditures (CapEx), to achieve their high levels of operating reliability and to comply with increasing regulatory

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[4] For example, Entergy cited low power prices and wholesale market design flaws as part of the reasons for its decision to shut down the Vermont Yankee, Fitzpatrick and Pilgrim nuclear plants (see Entergy press releases). Similarly, Dominion cited low power prices as a key driver in its decision to retire the Kewaunee nuclear plant (see Dominion press release).

requirements. Their high fixed costs are due in part to their large skilled staff requirements relative to other types of generators. These costs have been increasing over the last several decades. In some cases, this is because nuclear generating companies have invested in power uprates to increase the output from their plants, which can be costly. In addition, the average age of the current nuclear fleet is about 34 years, so substantial capital expenditures (to replace steam generators, for example) are often necessary if a unit plans to renew its operating license for another 20 years beyond its original 40 year license, as most are planning and approved to do. Cost increases and falling revenue erode operating margins and profits, and can reach the point where it becomes more economic to shut down a plant permanently than to sustain a prolonged period of financial losses.[5]

This problem is not unique to nuclear units; about 40 GW or 13% of U.S. coal-fired generating capacity has already retired since January 2012, primarily as a result of additional environmental compliance costs that coincided with an era of low wholesale power prices. Another 10% of coal capacity might retire by 2020 if energy market conditions persist and generation owners assess the prospects of future environmental compliance expenditures, including potential climate policy. While coal retirements reduce CO_2 emissions, much of the capacity that has recently retired had been operating at significantly reduced levels for several years. Because nuclear units operate continuously at maximum output, however, the generation lost per MW retired is much higher, and in that sense nuclear unit shutdowns have greater consequences for emissions and climate policy, and of course in the opposite direction, than the retirement of relatively underutilized coal plants.

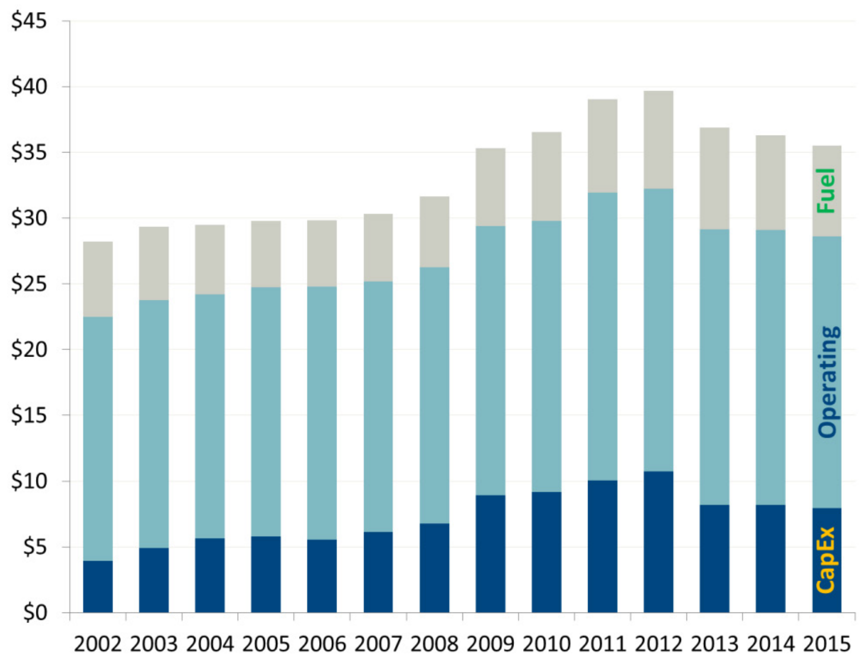
Nuclear plant costs (operating costs, maintenance and fuel costs, and CapEx) have increased over the last decade. According to data from the Electric Utility Cost Group (an industry organization that collects and aggregates detailed cost data from electric generators, including all U.S. nuclear generating companies), nuclear fuel costs rose by 21% cumulatively between 2002 and 2015, and O&M costs increased by 11% in real terms, as shown in Figure 2. The largest increase over this timeframe has been in capital spending, which has increased by over 100%—from $3.92 per

5 An extended temporary but not permanent shutdown—"mothballing"—to avoid losses in a down market is not typically an option for a nuclear plant. A nuclear plant's variable costs are small and would amount to little savings, with the specialized labor needed to run a nuclear plant accounting for most of its fixed operating costs. The need to maintain this staff means that little of the fixed costs could be avoided by mothballing. So even if power revenues are insufficient to cover full costs, temporarily sacrificing all revenue while retaining a large share of costs makes this option impractical.

MWh in 2002 to $7.97 per MWh in 2015 (in constant 2015 dollars)—though it is down from the higher levels observed a few years earlier.

Capital spending in the nuclear power industry may be somewhat cyclical, with periodic peaks. Most of the U.S. nuclear fleet was built in a relatively short period of time, resulting in periodic surges in capital spending as plant equipment is replaced and upgraded on normal life-cycle schedules. About one-third of total capital expenditures in 2014 went to fund power uprates, steam generator and vessel head replacements, and additional items necessary for license renewal and operation beyond 40 years. Routine equipment replacement accounted for another third of the total and has been relatively flat recently. CapEx to comply with the Nuclear Regulatory Commission's regulations and requirements was almost one-third of the total, a share that has more than doubled in the last decade but, with Fukushima-related costs largely behind the industry, regulatory CapEx will likely decline going forward.

Figure 2: Annual Average Nuclear Plant Costs (2015 $/MWh)



Source: NEI

The average aggregate costs shown in Figure 2 do not convey the distribution of costs among different nuclear plant configurations. For example, while the 2015 average total cost is $36/MWh, a newer, larger multi-unit station might operate at a cost closer to $25/MWh. At the other end, a typical smaller, older, single-unit plant might cost $45/MWh. Combining the distribution of operating costs with the range of regional capacity and energy prices shows that most units are operating in the black, while a costly single-unit plant in a depressed market might experience a shortfall that approaches \$20/MWh. Of the units that are experiencing a shortfall—that is, among those with higher than average operating costs in a below average market—a representative operating deficit would be about \$10/MWh.

D. Retirement Decisions

Understanding the financial risk faced by a nuclear plant is more complex than comparing its fuel, operating and maintenance costs, and capital expenditures with the short-term market revenues it could earn. Even plants in a weak market and/or with high costs may not necessarily face imminent financial pressure. Indeed, roughly half of nuclear plants are still under state regulation and can continue to recover most or all of their costs through regulated rates; they are generally protected from a temporary down market. And even many merchant nuclear plants may be shielded temporarily from short-term market forces if they have hedged their output forward for a few years at higher (past) prices, or if they have a power purchase agreement (a long-term output contract) that guarantees them a sufficient price. However, when those contracts expire or come up for renewal, the market risk can become quite immediate for a merchant plant. For instance, Dominion decided to retire the Kewaunee plant when its output contracts expired at the

Zero Emissions Credits under New York's Clean Energy Standard

As an example of a mechanism to preserve threatened nuclear plants, New York's Clean Energy Standard, recently ordered by the New York PSC, contains a support provision for the upstate New York nuclear plants in the form of Zero Emissions Credits (ZECs), which will be available to these nuclear plants under long-term contracts to 2029. Based on the federal Social Cost of Carbon (SCC) estimate of \$42.87/short ton in the near term, and excluding the implicit carbon value already captured in power prices by virtue of the Regional Greenhouse Gas Initiative (RGGI) carbon cap, the ZEC payments for the upstate nuclear plants amount to \$17.48/MWh initially. Going forward, this ZEC value will be adjusted as the SCC changes over time, and reduced by the amount of any increase in the market price of power from its current level. On the basis of this ZEC support, the Fitzpatrick plant, which had been scheduled for premature retirement in January 2017 by its owner, Entergy, will be taken over by Exelon, which will operate it for the remainder of its license life to 2034. The other two upstate New York plants, Ginna and Nine Mile Point (units 1 and 2), are already owned by Exelon, which had said they would be shut down in the near term without some form of financial support, but now plans to operate them for the remainder of their current license lives, which have been extended to approximately 60 years by license renewals. However, the ZEC program is currently being challenged in a federal lawsuit by a coalition of fossil generators.

end of 2013, and Dominion found that it could not replace the contracts at comparable prices or even find a buyer for the plant in the face of low wholesale market prices. This was despite the fact that Kewaunee had just been granted a 20-year extension of its operating license and was operating at high availability and capacity factors.

Beyond hedges or other financial immunization on the revenue side, the retirement decision is complex for other reasons, including whether any current shortfalls are likely to be offset by deferred, longer term gains if/when prices and margins recover, as well as the timing and magnitude of fixed costs (such as decommissioning) that may be accelerated by premature shutdown. But none of these tradeoffs even need to be considered when current operating margins are robust (see the sidebar on the recent New York solution that should resolve any concerns about premature shutdown for the upstate New York nuclear plants). A similar solution was recently reached in Illinois for troubled nuclear plants there.

III. The CO_2 Impacts of Nuclear Retirement

U.S. nuclear units operate as baseload resources, producing at maximum capacity on a continuous basis. When a nuclear plant retires, other resources must increase their output to replace the energy that it previously provided. Since existing renewable generators are already producing as much as possible given the availability of the resource (*e.g.*, wind or sun), they generally cannot provide the power to replace a retiring nuclear plant. Instead, the replacement power will come from existing dispatchable fossil capacity—gas or coal-fired generation, and possibly by new gas capacity, to the extent existing capacity is insufficient. Thus, the emission rates of the next most economic fossil capacity not yet being dispatched in the regional market will determine the CO_2 emissions that arise from replacing a retiring nuclear unit.[6] The incremental emissions per lost nuclear MWh can be used to determine an implicit price for carbon that would motivate the nuclear plant to remain operating, if it was experiencing financial shortfalls of a given level such as $10/MWh. Translated into units of $/ton of CO_2 avoided by forestalling a nuclear retirement, this figure can be compared with the cost of alternative ways carbon abatement options.

In principle, each nuclear plant could have a unique signature in terms of the emissions that arise as a function of its retirement. In practice, similarly-sized nuclear plants within a given region will have very similar impact, since the replacement resources will be very similar for each.

6 This is subject to transmission flow feasibility, which increases the complexity of identifying the marginal sources of replacement power.

However, retiring a nuclear plant in one region may have a significantly different impact than retiring a similar unit in a different region, because the generating resources used to replace the power—and their CO_2 emissions—will differ, sometimes substantially. Below we simulate several different regions to show how the retirement of a 1,000 MW nuclear unit would affect overall CO_2 emissions, as well as the geographic distribution of those increased emissions.

The simulations reveal that a nuclear shutdown would have substantial impacts on emissions in adjacent and remote states, which has implications for attaining state-level emission goals, whether those goals may be set by the state itself, or are part of a broader national policy such as the EPA's CPP or a potential successor policy. The replacement generation—and the CO_2 emitted by that generation—will not necessarily (in fact, will not generally or even mostly) arise in the home state of the retiring nuclear plant, or even in adjacent states, and some of the replacement energy may even come from beyond the plant's co-dispatched broad market region. In many cases, fossil-fired generating units hundreds of miles away will increase their output in response to demand and price signals that originate from the retirement of a given nuclear plant.

E. Modeling Approach

Recognizing the complexity of the decision to prematurely retire a nuclear unit, we adopted a generic perspective for the analysis. We did not assess the vulnerability of individual nuclear units, but rather estimated the annual CO_2 impacts of removing 1,000 MW of nuclear capacity from selected regions in the U.S., without explicit regard to the market outlook, operating costs or resulting economics of any particular nuclear unit in that region. We developed a multi-regional model of the Eastern Interconnection and the Electric Reliability Council of Texas (ERCOT) to assess the magnitude and location of CO_2 emissions that would result from the premature retirement of a nuclear generator in various locations.

We used a proprietary power system simulation model, Xpand, to simulate near-term power market operations and resulting prices, emissions, and technology mix in order to examine a variety of public policy questions, selecting 2017 as the base year for our analysis of the Eastern portion of the U.S.[7] We selected several broad regions within the Eastern Interconnection, and simulated the hypothetical retirement of a 1,000 MW nuclear plant in each of these regions.

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7 We ran the Xpand model for the Eastern Interconnection as a whole and separately for ERCOT. Xpand is a regional production simulation and capacity expansion model that finds the least cost generation mix and operation over time to meet load within and across regions that are connected through transmission links.

Table 2 below summarizes the nuclear fleet in these six broad regions within the Eastern Interconnection, along with ERCOT.

Table 2: Regional Breakdown of Nuclear Retirement Analysis

Region for Analysis	Electrical Regions	Number of Nuclear Units	Total Nuclear Capacity (MW)	Nuclear Share of Capacity	Nuclear Share of Generation
New York and New England	NYISO, ISONE	10	9,296	13%	27%
Mid Atlantic	PJM (except PJM-ROR)	13	13,702	22%	43%
South Atlantic	VACAR, TVA	18	18,216	21%	23%
Midwest (Eastern)	PJM-ROR	20	20,047	17%	29%
Midwest (North, West)	MISO, SPP	13	9,936	5%	7%
Southeast and South Central	SOCO, ENT, FRCC	15	14,410	9%	14%
Texas	ERCOT	4	5,131	5%	12%

We analyzed the effect of a nuclear retirement in each region, comparing overall fossil generation and CO_2 emissions with and without the nuclear retirement, and tracking the location of the replacement generation and associated CO_2 emissions.

F. MODELING RESULTS

Table 3 below summarizes our results for the seven regions analyzed, which are labeled on the left along with the home state of the nuclear unit whose "retirement" was simulated. The total increase in CO_2 emissions across all regions is displayed in the next column, and the rightmost column shows the aggregate emission coefficient (the amount of CO_2 avoided by each nuclear MWh in that region). [8]

[8] In the case of Illinois, which is split between two RTOs, we conducted an experiment where we retired a different Illinois nuclear plant, in the other RTO market area (*i.e.*, MISO), and found very different overall emission impacts and geographic patterns. This illustrates that nuclear retirements even in the same state can exhibit differing impacts, adding a further complication to pursuing a state-level approach to reducing CO_2 emissions through retaining nuclear capacity.

Table 3: CO_2 Impact of a 1,000 MW Nuclear Retirement in Selected States

Region of Analysis	State	Total Increase in CO_2 Emission (million tons)	Total Increase in CO_2 Emission per MWh (tons/MWh)
New England and New York	CT	4.10	0.52
Mid Atlantic	PA	4.59	0.58
South Atlantic	SC	6.64	0.84
Midwest (PJM)	IL	5.75	0.73
Midwest (MISO)	MI	6.66	0.84
Southeast and South Central	AR	6.14	0.78
Texas	TX	5.17	0.66

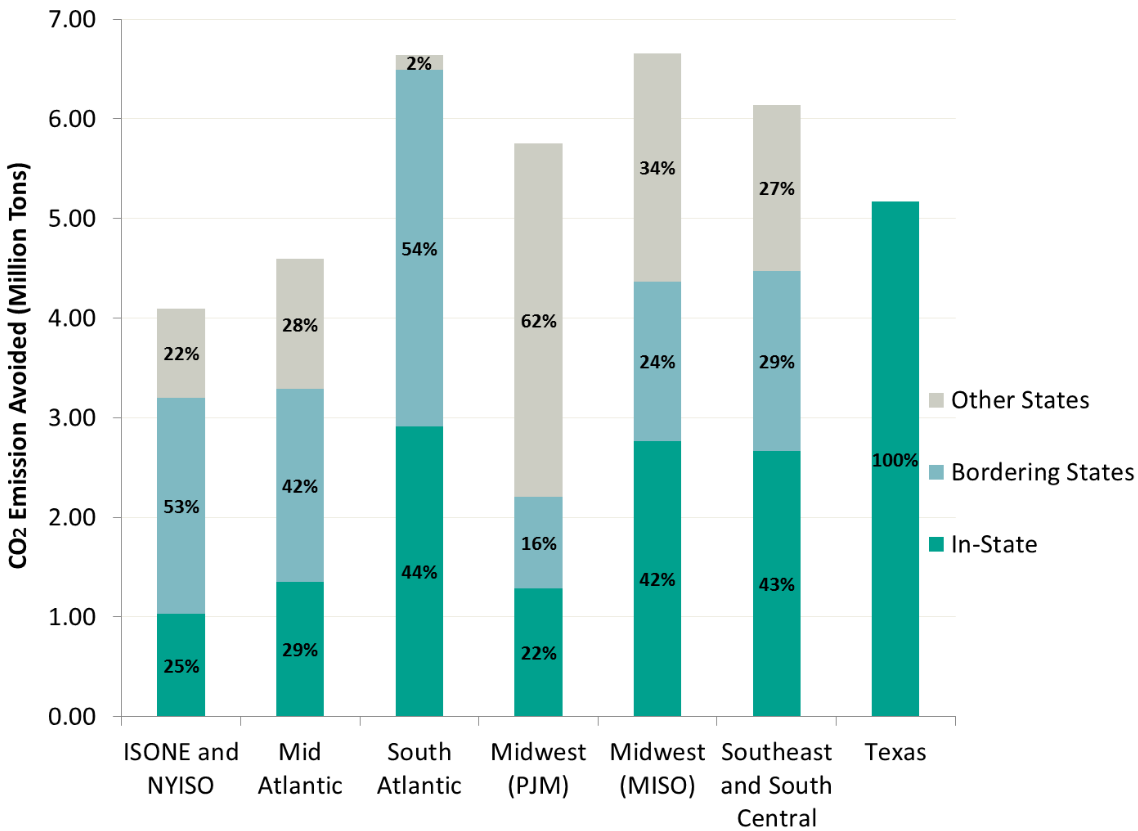
As Table 3 shows, the magnitude of the CO_2 emission effect varies substantially across market regions. For example, a nuclear retirement in South Carolina or Michigan has about 1.6 times the carbon effect of an equivalent nuclear retirement in Connecticut. This is because in some regions, a nuclear plant's output will be replaced primarily by coal generation, while in others the replacement will be mostly natural gas. Since those technologies differ by roughly a factor of two in CO_2 emission rates, this results in a wide range of emissions increases from nuclear retirements in different regions, and a commensurate range in the emissions savings expected from retaining nuclear capacity. This may motivate policies that take into account the likely emissions effects in designing policies to retain nuclear plants.

In addition to the absolute magnitude of CO_2 emission increases, we also analyzed their geographic distribution. Figure 3 displays the percentages of the total emission increases that occur within the state, in adjacent states, and in the broader region beyond. This shows that the geographic dispersion of the CO_2 emission effect differs markedly by region, but consistently only a relatively small portion of the emissions increase occurs in the home state of the retiring nuclear plant, with the bulk of the emissions impacts occurring in neighboring states and farther afield. ERCOT is an exception, but in every other region, more than half the incremental CO_2 emissions would come from outside the retiring nuclear plant's home state.[9] At the extreme, 62% of the CO_2 footprint from replacing a retiring nuclear plant could come from states not even adjacent to the retiring plant's home state. This provides a graphic illustration of the wide-

[9] The majority of Texas is within the ERCOT ISO, which is not synchronously interconnected with the rest of the United States, so a nuclear retirement in ERCOT would not have significant effects beyond Texas.

ranging emissions implications that propagate across state lines and throughout broad regional power markets in response to a nuclear retirement. Therefore, a climate policy that involves state-specific targets, as the CPP does, can result in a nuclear shutdown in one state making it more difficult for other states to comply with their CO_2 reduction targets.

Figure 3: Geographic Breakdown of Emission Increases



IV. Cost of CO_2 Abatement from Retaining Existing Nuclear Plants

Existing nuclear generating plants provide CO_2-free baseload generation around the clock, while the fossil generation plants that provide the system's marginal hourly energy needs emit CO_2 to varying degrees, depending on the generator's fuel type and efficiency. As discussed in the previous section, the CO_2 emission impact of losing nuclear generation is typically in the range of 0.52-0.84 tons per MWh, and varies by region.

To the extent a nuclear plant may be unable to recover its full going-forward costs from wholesale power market revenues, it could face premature economic retirement. Over the last few years, three nuclear plants have been retired for economic reasons, and three more have recently announced that they will retire in the next several years. Such retirements might have been avoided (or more importantly, future nuclear retirements might be preventable) if there were some market or regulatory mechanisms by which a nuclear plant could capture at least part of the value of the CO_2 emissions that it prevents. Table 4 below examines a hypothetical nuclear revenue shortfall of $10/MWh (*i.e.*, the gap between power market revenues and nuclear going-forward costs), which is representative of the revenue deficits experienced by vulnerable merchant nuclear plants recently. Most wholesale power markets where merchant nuclear plants are operating have recently had all-hour prices (including capacity payments, where available) of around $25 to $50/MWh, while some older or single unit nuclear plants had combined fuel, fixed O&M, and CapEx costs that were about $20 above the lower end of that price range; other vulnerable plants had much smaller shortfalls. The table shows the implied value of avoided CO_2 that would cover the $10/MWh revenue shortfall, calculated as the assumed revenue deficit divided by the regional CO_2 intensity factor—which accounts for the fact that a significant share of the replacement power would come from outside the vulnerable plant's home state.

Table 4: CO_2 Abatement Cost of Retaining Existing Nuclear Plants with $10/MWh Shortfall

Region	Regional CO_2 Intensity (tons/MWh)	CO_2 Abatement Cost of Retaining Nuclear Plants ($/ton)
Midwest (North, West)	0.84	$11.84
South Atlantic	0.84	$11.87
Southeast and South Central	0.78	$12.84
Midwest (Eastern)	0.73	$13.71
Texas	0.66	$15.26
Mid Atlantic	0.58	$17.17
New York and New England	0.52	$19.24
Average	0.71	$14.56
Range	0.52 - 0.84	$11.84 - $19.24

As shown in the table above, the cost of avoiding CO_2 emissions by retaining an existing nuclear plant that faces a representative $10/MWh revenue shortfall range roughly from $12/ton to almost $20/ton, depending on the region. The avoided CO_2 cost is the lowest in regions (*e.g.*, Midwest and South Atlantic) where CO_2-intensive coal plants are typically the marginal source of energy, and is somewhat higher in regions like Texas, the Mid-Atlantic, and the Northeast where lower-carbon natural gas is usually the alternative energy source. To put this in perspective, to make up $10/MWh for a 1,000 MW nuclear plant would cost about $80 million per year. In a market with an all-hours average price (capacity and energy) of $45/MWh, such as PJM West in 2015, the plant's electricity output would be valued at roughly $360 million per year with no CO_2 emissions, and total PJM West generation would be valued at $4.5 billion annually. In addition, this cost range of $12-20/ton of avoided CO_2 emissions is comparable to or lower than many alternative CO_2 abatement policy options.[10]

V. Nuclear Retirements and Climate Goals

To illustrate the potential impact of premature nuclear plant retirements on CO_2 reduction goals, we estimated the increase in CO_2 emissions that would result from the retirement of announced and "at risk" units in the Eastern Interconnection, as identified by industry analysts.[11] The units analyzed include Pilgrim (Massachusetts), Fitzpatrick (New York), Clinton and Quad Cities 1 and 2 (Illinois), and Oyster Creek (New Jersey), all of which have recently been announced for retirement over the next few years, as well as other plants in Illinois, Kansas, Louisiana, Michigan, Pennsylvania, Minnesota, Ohio, South Carolina, and New York.[12] These 19 units have a total capacity of approximately 15,500 MW and historical annual generation of about 122 million MWh.

In aggregate, the loss of these "at risk" units would increase near-term emissions by about 88 million tons per year, which is about 5% of the current total CO_2 emissions from the electric sector. As a result, compliance with any annual emissions target would require an additional 88 million tons of annual CO_2 reductions elsewhere, adding to the difficulty and cost of attaining these targets. Further, it would almost certainly involve higher emissions for an interim period, even if the same eventual annual goal could be reached, and this would increase cumulative CO_2 emissions, which are what drive climate effects. The emissions effect is greater in the regions

10 For example, EPA estimated the carbon cost of heat rate improvements at less than $23/ton, coal-to-gas switching to reach 75% capacity factor at existing gas-fired units at $24/ton, and adding new renewable generation at $37/ton (see Greenhouse Gas Mitigation Measures, U.S. EPA Office of Air and Radiation, August 3, 2015). EPA estimated the carbon cost of energy efficiency programs at $16-24/ton (see Demand-Side Energy Efficiency Technical Support Document, EPA, August 2015).

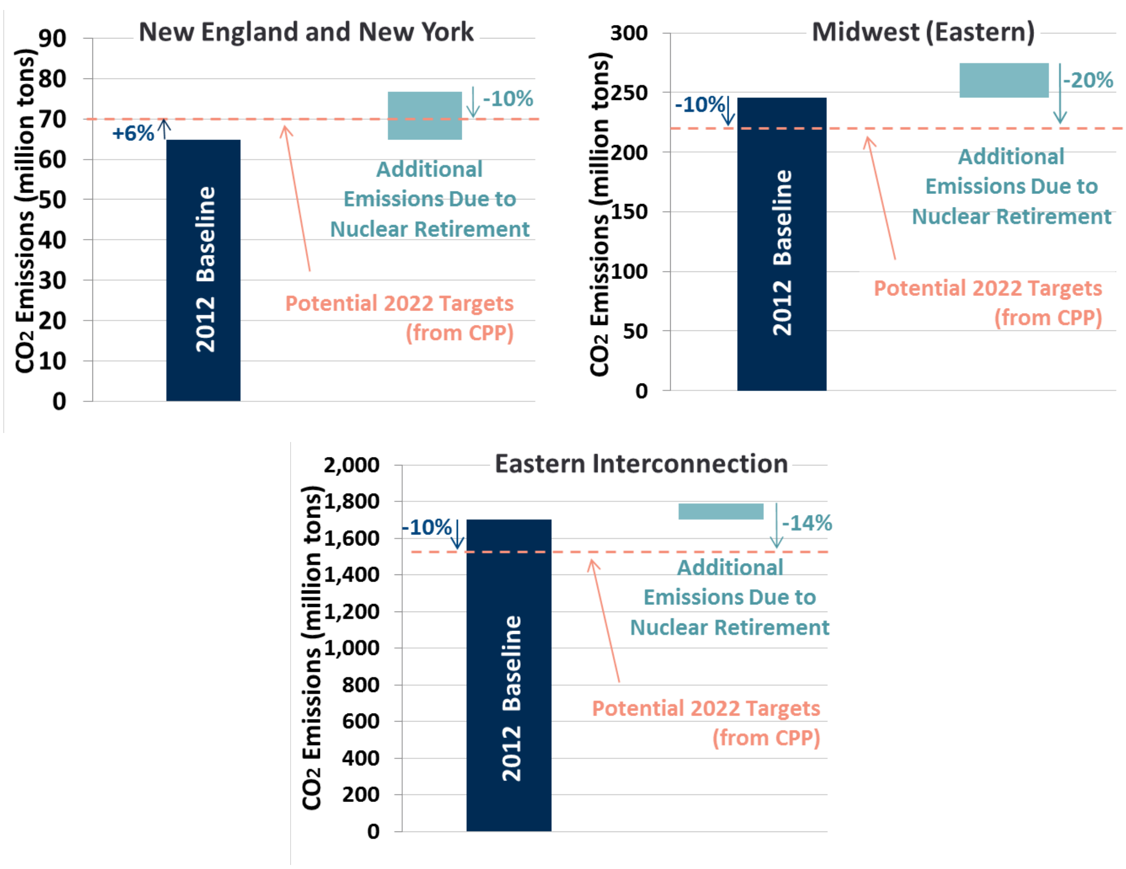
11 UBS, Moody's and Fitch Ratings, as summarized in an SNL article, "As Pilgrim falls, 11% of nuclear generation at risk of early closure," October 16, 2015; also SNL's estimate of at-risk units in "More than 21 GW of coal, gas and nuclear capacity 'at risk' of retirement," July 5, 2016.

12 Several of these nuclear units, notably the upstate New York units and the Illinois units, will be supported going forward by recent state-level responses to prevent their closure. This analysis is a hypothetical illustration of the potential effects of not supporting all these at-risk nuclear plants.

where the "at risk" nuclear units are located, though is not limited to the particular states in which they reside.

To illustrate, Figure 4 compares, for two regions and for the Eastern Interconnection as a whole, 2012 baseline emissions, the emissions increase that would accompany the early retirement of the "at risk" units, and a potential medium-term emissions reduction goal—here using the 2022 CPP target to illustrate a potential policy goal. The upper left panel shows that "at risk" nuclear retirements would cause New England and New York to switch from being in aggregate already 6% ahead of the 2022 CPP targets, even in 2012, to needing a 10% emission reduction in order to meet the targets if the at risk nuclear plants were to retire. Similarly, in the Midwest (Eastern) region that covers the PJM territory outside MAAC, these nuclear retirements would make it necessary to reduce CO_2 emissions by 20% rather than 10%. In the Eastern Interconnection as a whole, nuclear retirements would increase the required CO_2 cuts from 10% to 14%.

Figure 4: Impact of 16 GW of Premature Nuclear Retirements on CO_2 Emissions



G. Geographic Effects Challenge State-Level Policy Responses

Despite the clear increases in aggregate emissions and potential climate policy compliance costs that would result from premature nuclear retirements, the dispersed geographic patterns of the emission impacts can inhibit the development of state-level policies to cost-effectively retain nuclear capacity. This is true for a policy that is state-initiated, but is also true for any national policy that would be implemented through state-level emissions targets. In either case, since the emissions target is identified at the state level, the need to preserve a threatened nuclear plant is generally perceived as being the responsibility of the state where the plant is located. But as was illustrated graphically in Figure 3 above, a premature nuclear retirement in one state will generally have significant emissions impacts in other states and regions, because most regions have integrated, interstate power markets that cover broad geographic areas. This means that the increased compliance costs of failing to preserve the plant will be spread across other states, mostly outside the home state of the at-risk plant. Depending on the structure of the policy, this might require increased CO_2 abatement in those other states, or if the policy allows interstate trading, could significantly increase the price of the traded allowances across all the states in the common trading system.

In either case, this separation of responsibility and benefits can complicate the challenge of devising state-level policy responses. When the emissions impact is widespread, much of the benefit of a state-level policy response to prevent a nuclear retirement will flow to other states. To the extent existing nuclear plant owners or the states in which they reside do not earn allowances, carbon value, or other credit for continuing to operate, as is the case with the CPP, there may not be a ready mechanism to overcome this misalignment of incentives and impacts.

H. Option Value of Retaining Existing Nuclear Capacity

Premature retirement of nuclear capacity will raise CO_2 emissions immediately, and will make compliance with any state or national climate policy either more costly or less effective, or both. These impacts arise regardless of what it would actually cost to retain the nuclear capacity in the near term, and will persist for what would otherwise have been the remaining lifetime of the nuclear unit. Since owners will make retirement decisions based on private economics rather than overall societal cost-effectiveness, the question naturally arises: given the permanence of premature nuclear retirement and the long-term effect on emissions and abatement costs, is there public “option value” in preserving nuclear capacity for its future carbon abatement that may exceed the value a private owner might capture?

Under many likely future circumstances, there is option value to preserving existing nuclear plants as an emission-free generation resource in the transition to a carbon-constrained future. For example, there is the potential for future implementation of climate policy in a form that creates an effective carbon price uplift in wholesale markets, the potential for increases in natural gas prices, and potential barriers to achieving energy efficiency savings. Private nuclear owners can certainly withstand some losses[13] in the near term if they expect that their margins will improve in the future; this is private option value. However, owners may be unable or unwilling to retain vulnerable nuclear capacity for the potential societal benefits of reduced emissions that they are unlikely to capture themselves. The overall social costs of meeting emissions goals will depend partly on the availability of the existing nuclear fleet, creating this divergence between social and private costs that can lead to the "wrong" decision—a situation that has arguably already occurred in several instances.

VI. Conclusion

Nuclear operating costs, considering only ongoing costs (fuel, operating and new capital) and not the recovery of past investments, averaged approximately $36/MWh in 2015, with single-unit nuclear plants (like the recently-retired Kewaunee, Vermont Yankee, and Fort Calhoun plants) operating at costs of about $45/MWh. The owner of a nuclear plant that is unable to recover at least these ongoing costs from market revenues may choose to retire the plant prematurely, rather than continuing to operate at a loss. The recent fall in power prices has made this an immediate concern for a number of nuclear plants—those with relatively high costs and/or those in markets with lower power prices—jeopardizing their financial viability. Three nuclear plants have retired prematurely in the last several years due solely to such economic factors, three more have recently announced that they will retire soon, and a number of others are facing similar risks.

But the loss of a nuclear plant would cause a significant increase in CO_2 emissions, at a time when it is important to cut emissions levels. And it would affect not only current CO_2 emissions: because the shutdown is irreversible, it would also mean the loss of many future years of CO_2 abatement. This would mean more GHGs would be in the atmosphere sooner, increasing climate risk and complicating the transition to a low-carbon energy sector. In particular, it would make

13 For example, Exelon indicated in an earnings release in May 2016 that it incurred about $800 million cash flow losses at the Quad Cities and Clinton nuclear plants over the period 2009-2015. See Exelon's Earnings Conference Call, 1st Quarter 2016, May 6 2016, page 7.

compliance with any future climate policy more difficult and more costly. The adverse implications would also likely extend well beyond the boundaries of the home state of the retiring plant, since much of the replacement generation will come from fossil plants in surrounding or more remote states. This could increase emissions and/or the demand for and price of tradable credits and allowances in those states.

Offset against this is the fact that despite their financial difficulties, the actual near-term shortfall for a distressed nuclear plant tends to be relatively modest—typically around $10/MWh, which translates to $12 to $20 per ton of avoided CO_2, depending on the size of the shortfall and the carbon-intensity of the affected region. In addition, the overall avoided CO_2 costs may be considerably lower than this, since the need for support costs may be only temporary, with a few years of support needed in the near term to preserve significant CO_2 savings for many years to come. A meaningful and efficient program for interim support of nuclear plants that might otherwise face premature economic retirement represents a cost-effective component of a policy to reduce long run CO_2 emissions.

This is not to suggest that existing nuclear plants are in competition with renewable generation or end-use efficiency improvements in terms of the ability to abate carbon emissions or the cost of doing so. On the contrary, many types of low- or no-carbon resources will be necessary to achieve significant carbon reductions in the long run. However, it is important to recognize that nuclear generation is a very large and relatively low-cost source of carbon offsets that is available immediately. Losing the at-risk nuclear generators considered in Section VI above would wipe out about twice the CO_2 benefits provided by all the currently installed U.S. solar capacity, even considering its recent high growth. If additional nuclear plants retire prematurely, it could make it difficult (and quite costly) to regain the lost carbon abatement with other resources. Given the magnitude of the long-run emissions cuts that ultimately will be required, it will make sense to retain as much reasonably-priced zero-emission generation as possible. This will limit the level of emissions in the near term, prior to the implementation of a comprehensive climate policy, and make it more likely and less costly to achieve those policy goals in the longer term.

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