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Assessing the impact of nuclear retirements on the U.S. power sector

James Richards[a,*], Wesley J. Cole[b]

[a] Strategic Energy Analysis Center, National Renewable Energy Laboratory, Golden, CO 80401, United States
[b] University of Idaho, 1776 Science Center Drive, Idaho Falls, 83402, United States

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ABSTRACT

This work utilizes the Regional Energy Deployment System (ReEDS) model to analyze the impacts of four nuclear retirement scenarios of the U.S. electricity sector, from nuclear plant lifetimes of 50 to 80 years. The analysis finds that longer nuclear lifetimes decrease the amount of renewable and natural gas capacity. Longer nuclear lifetimes also resulted in lower cumulative and annual carbon emissions, lower transmission builds, and higher energy curtailment and water usage.

1. Introduction

Nuclear power has been a part of the U.S. generating mix since the Shippingport Atomic Power station was connected to the grid in 1957 (DOE, 1994). Nuclear power then saw nearly 40 years of rapid expansion followed by nearly 20 years of no growth (Fig. 1). Of the 99 currently operating reactors, 92 were built prior to 1990 (ABB, 2017). These 99 reactors are spread across 61 nuclear power plants, with individual plants housing one to three reactors. Nuclear plant operating licenses are initially issued for 40 years of plant operation. Of the 99 reactors at the 61 nuclear plants in the U.S., 84 have already extended their operating license from 40 to 60 years, while 13 more have filed or announced their intent to file for a 20-year license renewal (NEI, 2017b). Two plants, Peach Bottom and Surry, have announced their intent to seek a second 20-year license renewal, or Subsequent License Renewal (SLR), which would give them the ability to operate for up to 80 years (NRC, 2017). In 2016, nuclear plants produced 20% of the nation's electricity and accounted for nearly 10% of the capacity.

Recently, several nuclear plants have had difficulty remaining profitable. Steckler (2017) estimates that about half of U.S. nuclear reactors are currently losing money. A similar analysis performed by Haratyk (2017) found that as many as 38 out of 61 plants would not be profitable from 2017 to 2019. Some states, such as Illinois and New York, have passed legislation to financially support nuclear power plants within their states in order to prevent early retirements. Other states, including Pennsylvania, Ohio, and Connecticut, are considering similar proposed legislation (Maloney, 2017).[1] Despite these efforts, five nuclear plants have retired in the last five years and an additional six plants have announced retirement dates (CEE, 2017; ABB, 2017). Table 1 lists the nuclear plants that have recently retired and or have announced retirement dates.

As seen in Table 1, seven of eight plants with announced retirement dates operate in restructured markets.[2] Power plants in restructured markets collect revenue from the competitive electricity markets that exist in their region (e.g., energy, capacity, ancillary services), and this revenue must be sufficient to cover all the costs of the power plants. With natural gas prices below $4/MMBtu, wholesale electricity prices are between $30 and $35/MWh (Haratyk, 2017). The average cost of nuclear generation is $35.5/MWh (NEI, 2016), meaning that many reactors would not be collecting sufficient revenue from the energy market to cover their costs.[3] Roth and Jaramillo (2017) find that nuclear plants are currently operating at a deficit of $8-$44/MWh from breakeven prices. In contrast, power plants in traditional regulated markets have their costs covered based on approval from the local regulatory body, such as a public utilities commission, such that power plants in a regulated market typically do not experience a change in "revenue" as market conditions change.

Another aspect that can impact the relative competitiveness of nuclear plants is whether or not the plant is a single-reactor or multi-reactor plant. Generating costs of multi-unit plants are, on average,

* Corresponding author.
E-mail address: rich2057@vandals.uidaho.edu (J. Richards).

[1] Not all state-specific actions have been in favor of keeping nuclear plants online. The retirements of the Diablo Canyon and Indian Point power plants have been encouraged by some state actors for a host of complex reasons.

[2] Market structures are much more complex in reality, dependent on individual owners, operators, states, etc. The simplification of markets to either traditional or restructured structures is sufficient for this work.

[3] This type of economic pressure was demonstrated recently when Three Mile Island and Quad Cities plants failed to clear the capacity auction in PJM. In response, the owners announced that Three Mile Island would retire in 2019.

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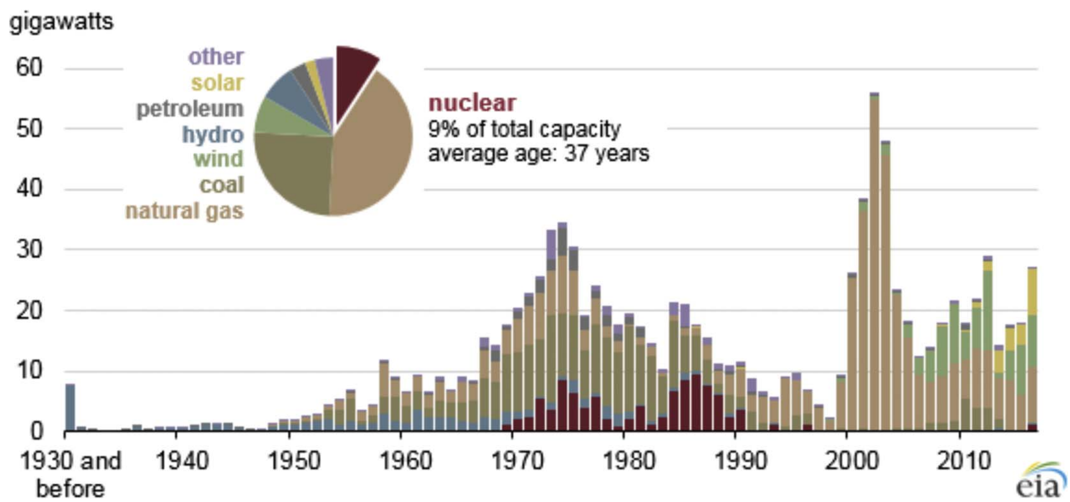

Fig. 1. U.S. electricity sector generator capacity by initial year of operation (EIA, 2017b).

Table 1
Recent and announced nuclear retirements (ABB, 2017). The retirement years shows the retirement date for each reactor located at the plant.

Plant Name	State	Capacity (MW)	Retirement Year	Market Structure
Crystal River	FL	838	2013	Traditional
Kewaunee	WI	566	2013	Restructured
San Onofre 2 & 3	CA	2250	2013/2013	Traditional
Vermont Yankee	VT	619	2014	Restructured
Fort Calhoun	NE	502	2016	Traditional
Palisades	MI	789	2018	Restructured
Pilgrim	MA	678	2019	Restructured
Oyster Creek	NJ	636	2019	Restructured
Three mile Island	PA	803	2019	Restructured
Indian Point 1 & 2	NY	2060	2021/2022	Restructured
Diablo Canyon 1 & 2	CA	2300	2024/2025	Traditional

Table 2
Nuclear generation cost in single vs multi-reactor plants (NEI, 2017a).

	Fuel ($/MWh)	Capital ($/MWh)	Operating ($/MWh)	Total Generating ($/MWh)
U.S. Average	6.91	7.97	20.62	35.50
Single-Unit	7.10	10.26	27.15	44.52
Multi-Unit	6.85	7.31	18.74	32.90

$11.6/MWh less than single-unit plants (Table 2). Single-unit plants have higher operating costs because they require more employees per MWh. Additionally, single-unit plants do not have the ability to share capital-intensive systems, such as turbines or generators, over multiple reactors, which results in higher fixed costs per MWh. Of the planned and announced retirements listed in Table 1, 8 of 11 are single-reactor plants.

Nuclear capacity currently makes up the largest source of carbon-emissions-free electricity in the U.S., providing over half of the country's carbon-free generation (EIA, 2017d). However, when nuclear plants are retired, they are often replaced by natural gas units, which typically result in an increase in CO_2 emissions. For example, in California, Florida, and Wisconsin, emissions rose after the retirement of nuclear facilities, specifically the San Onofre, Crystal River, and Kewaunee (Davis and Hausman, 2016; EIA, 2017c) plants. Furthermore, early nuclear retirements have been linked to increased consumer electricity prices (Berkman and Murphy, 2016) and decreased energy security (Watson and Scott, 2009). On the other hand, other studies have shown that nuclear plants lead to a more expensive electricity system (Lovins, 2013) and are unnecessary for energy decarbonization (Jacobson and Delucchi, 2011).

A number of studies explored the impacts of phasing out or retiring nuclear power. Bretschger and Zhang (2017) discuss a nuclear phase-out in Switzerland. The authors use a computable general equilibrium (CGE) model that pulls economic data from different sectors to analyze the economy-wide effects of phasing out nuclear. They find that a gradual, full phase-out in the most extreme cases can lead to welfare losses of 0.4%. Bruninx et al. (2012) perform a mixed integer optimization to minimize German electric sector costs while removing nuclear plants in 2012 and 2022, as prescribed in the *Energiewende* program. They found significant transmission congestion as Germany switched from being a net exporter to a net importer with the retirement of nuclear plants in 2012. They also found that high renewable scenarios had more emissions in the nuclear phase out than the business as usual case because a portion of nuclear power was replaced by lignite coal. Duscha et al. (2014) investigates the impacts of worldwide nuclear phase-out by 2020. They show that world greenhouse gas emissions would increase by 2%. U.S. emissions also increased by 2% in the phase-out scenario, while Japan saw the largest increase in greenhouse gas emissions at almost 7% (Duscha et al., 2014).

In the U.S., Haratyk (2017) projected that wholesale electricity prices would rise in the mid-Atlantic in a complete nuclear phase-out anywhere from $0.10/MWh to $1.26/MWh depending on the replacement generation. Jacoby and Paltsev (2013) studied two scenarios, an nuclear license renewal freeze and a forced retirement situation in which all plants are shut down by 2030. They found that, regardless of policy, the country would see an increase in emissions because most nuclear was replaced by natural gas. Brinton and Freed (2015) investigated three U.S. nuclear retirement scenarios that retired nuclear plants at 60-year life, 40-year life, or by 2025. They found that emissions increased in each scenario, with the complete phase-out seeing the largest increase. Brinton and Freed also find that renewables find have strong growth through 2035 but are not able to completely replace nuclear plants as they retire.

This work differs from previous studies in that it employs a least-cost capacity expansion model to investigate the long-term effects of several nuclear retirement scenarios on the U.S. electricity sector. Specifically, we consider the impacts of varying nuclear lifetimes on the need for new capacity, generation mix, power sector emissions, water withdrawal and consumption, and renewable energy curtailment. Section 2 describes the modeling tool and nuclear retirement scenarios we use in this analysis, and Section 3 presents the scenario results.