REPORT | ENERGY

Preserving America's Clean Energy Foundation

By Amber Robson | Published: 12/08/16

TAKEAWAYS

Nuclear power plants across the country are facing economic headwinds and are at risk of closure, threatening the foundations of America's clean energy progress. Taking action now to maintain the nation's nuclear reactor fleet is among the lowest-cost clean energy options available today and should be an essential component of U.S. clean energy goals. Here's why:

- More than half the U.S. nuclear fleet may currently be at risk of closure.
- These at-risk reactors constitute America's largest source of clean energy, generating nearly as much electricity as all wind, solar, and hydroelectric power plants in the country combined.
- If existing reactors retire prematurely, they are likely to be replaced predominately by natural gas-fired power plants, which will cause emissions to rise.
- In most cases, electricity produced by existing nuclear reactors is cheaper than alternative sources of clean energy, such as new wind or solar power.
- Today's power markets do not fully value the climate and grid benefits of America's nuclear fleet—something that state and federal policymakers should resolve, as they have for other important sources of clean energy like wind and solar.
- Fixing this would ensure that nuclear fulfills its vital role in national efforts to create a clean, reliable, and low-carbon grid.
- In addition to the climate and grid benefits, preserving these plants maintains thousands of jobs and billions in economic activity and federal and state tax revenue.

America's Clean Energy Foundation is Crumbling

The United States is on course to a clean energy future. Emissions of carbon dioxide (CO_2) from the U.S. power sector have dropped 20% since 2005 and are now at their lowest level since 1993.[1] Yet the very foundation of this clean energy progress is starting to crumble. Dozens of nuclear power plants across the country are facing economic headwinds and are at risk of imminent closure, threatening to undermine the nation's clean energy goals. Already, six nuclear reactors have closed permanently since 2013, and retirement plans have recently been announced for eight more reactors.[2] The closure of each one of these power plants is a huge step backwards for the country, representing the loss of enough clean energy to power a medium-sized city. In addition, the 99 nuclear reactors in the U.S. generate substantial domestic economic value— $40-$50 billion each year — with over 100,000 workers contributing to production. These plants represent half of that economic activity.[3]

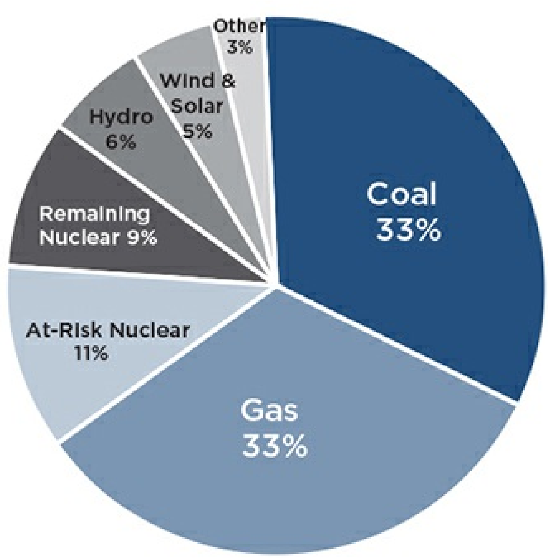
Table 1. Recent and announced retirements of U.S. nuclear reactors

Reactor	Size (MW)	Region	State	Owner	Age (yrs)*	Retirement Date
Crystal River 3	860	Southeast	FL	Duke Energy	36	February 2013
Kewaunee	556	MISO	WI	Dominion	39	May 2013
San Onofre 2	1,070	California	CA	SCE & SDG&E	30	June 2013
San Onofre 3	1,080	California	CA	SCE & SDG&E	29	June 2013
Vermont Yankee	620	New England	VT	Entergy	42	December 2014
Fort Calhoun	479	SPP	NE	Omaha PPD	43	October 2016
Fitzpatrick**	847	New York	NY	Entergy◊	42	2017 (p)
Ginna**	582	New York	NY	Exelon	46	2017 (p)
Nine Mile Point 1**	637	New York	NY	Exelon	47	2017(p)
Clinton†	1,065	MISO	IL	Exelon	29	June 2017 (p)
Quad Cities 1†	934	PJM	IL	Exelon	44	June 2018 (p)
Quad Cities 2†	937	PJM	IL	Exelon	44	June 2018 (p)
Oyster Creek	608	PJM	PA	Exelon	47	2019 (p)
Pilgrim	677	New England	MA	Entergy	44	June 2019 (p)
Diablo Canyon 1	1,118	California	CA	PG&E	31	2024 (p)
Diablo Canyon 2	1,122	California	CA	PG&E	30	2025 (p)
SUMMARY	4,665 MW closed		8,527 MW planned		13,192 MW total	

(p) planned retirement date
** Age reported at date of retirement for closed reactors; current age for operating reactors*
*** New York passed a Clean Energy Standard in August 2016 that will provide zero emissions credits to these facilities. If the standard survives legal challenges, these plants will continue operation.*
◊Entergy is in the process of transferring ownership of this plant to Exelon. The transaction should be finalized sometime in 2017.
†At the time of writing the State of Illinois had just passed a bill that would provide zero emissions credits for eligible nuclear generation for up to ten years. Assuming there are no regulatory challenges, these closure plans should be modified.

The full scope of the challenge is greater still. Cheap and plentiful supplies of American natural gas combined with slow growth in demand for electricity have led to very low prices for electricity in many parts of the country. This might be good news for U.S. consumers in the short term, but it could have far greater implications for climate goals and grid reliability in the long run. That's because record low wholesale electricity prices across much of the country are creating a situation in which more than half the U.S. nuclear fleet may be operating below the break-even point and face the risk of closure.[4] These at-risk reactors have a total capacity of 55,000 megawatts and reliably generate one in ten electrons in the country. To put it another way, the nuclear reactors now at risk of closure constitute America's largest source of clean power, generating nearly as much electricity as all wind, solar, and hydroelectric power plants in the country combined.[5]

Figure 1. 2015 U.S. electricity supply mix. At-risk nuclear power plants generate 11% of U.S. electricity, nearly as much as all wind, solar, and hydroelectric power combined.



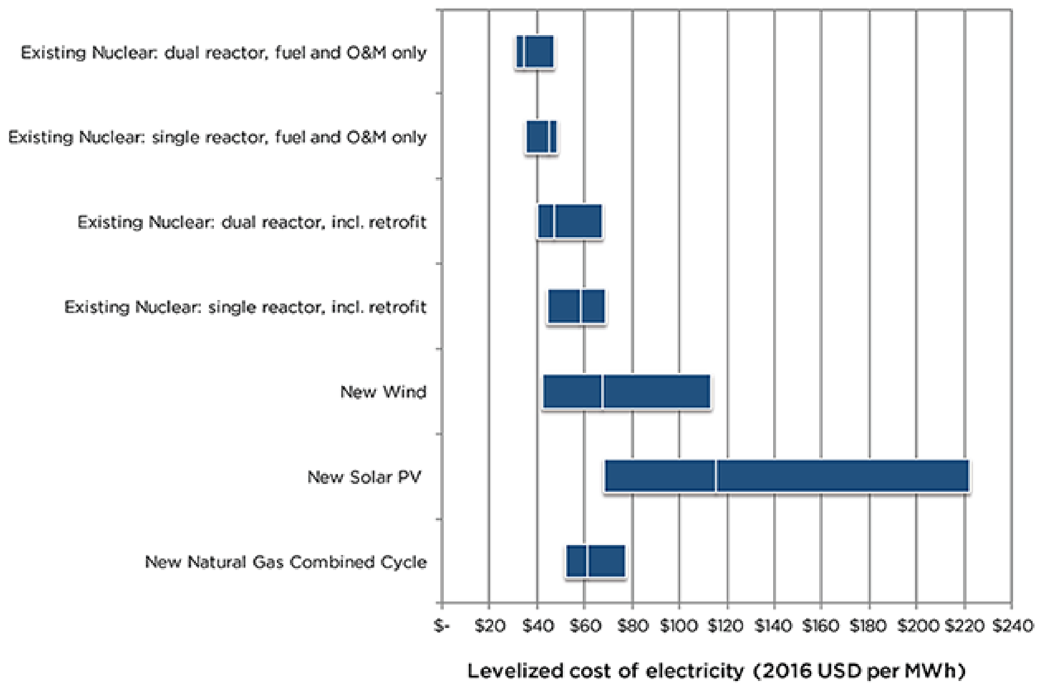
As Third Way's 2015 report, "When Nuclear Ends" demonstrated,[6] a wave of nuclear closures could undo recent progress in reducing power sector CO_2 emissions. Using an electricity capacity planning model developed by MIT-trained researchers, the report confirmed that when U.S. nuclear reactors retire, they are replaced predominately by increased generation from new natural gas-fueled power plants. That means greater CO_2 emissions as well as higher natural gas prices and more exposure to volatile natural gas markets for U.S. energy consumers.

To get a sense of the magnitude of the challenge, consider this: if the nation loses all 55,000 megawatts of nuclear power plants threatened by today's economic and policy landscape and those plants are replaced by new natural gas power plants, CO_2 emissions could increase by roughly 156 million metric tons annually.[7] That's 8 percent of total U.S. power sector CO_2 emissions in 2015 or the equivalent of the annual emissions from electricity consumption in 23 million American homes.[8] At a time when the United States is trying to move towards a low-carbon energy future, the country can't afford to lose this enormous share of our clean energy supplies.

America's Nuclear Fleet is an Affordable Source of Clean Energy

The good news is that, despite today's economic challenges, preserving the existing U.S. nuclear fleet is one of the most affordable ways for America to decarbonize its electricity sector. Based on industry and government sources, we estimate that existing nuclear power plants need to earn an average price of roughly $31 to $49 for each megawatt-hour (MWh) they generate to recover all of their operating costs, a figure known as the levelized cost of electricity (LCOE).[9] These costs cover the staffing, fueling, maintenance, and operation of existing reactors. Within this range, larger nuclear power stations with two or more reactors tend to cost less than single reactor power plants due to economies of scale (see Figure 2).

Figure 2. The "levelized cost of electricity" of existing nuclear power plants and new wind, solar and natural gas plants, 2016. This metric expresses the average pre-tax revenue a power plant needs to earn per MWh of electricity generated in order to recover all of its costs.



Estimates reflect the unsubsidized cost of each resource. For sources and assumptions, see Endnote [10]

Some of these plants may require capital investments to replace aging components or perform other upgrades, which can cost hundreds of millions of dollars or more. Yet despite the large price tag, these nuclear power plants will generate massive amounts of electricity. Any necessary upgrades would thus add just a few dollars to the cost of each MWh of electricity produced by nuclear reactors. We estimate that the LCOE of existing reactors requiring significant upgrades to remain operational could range from about $40 to $69 per MWh.[11] In addition, these retrofits often include upgrades that allow the nuclear reactors to produce more power than before (a process known as "uprating"), which would lower the LCOE even further than this estimate.

At an estimated cost of $31 to $49 for most reactors and up to $69 per MWh for plants requiring major upgrades, existing nuclear plants are among the most affordable sources of clean electricity available. Based on industry and government analysis, we estimate the unsubsidized cost of new wind power plants ranges from about $42 to $113 per MWh, depending largely on the quality of the wind resource available at different locations.[12] After several years of substantial reductions, the unsubsidized cost of large, "utility-scale" solar photovoltaic projects now ranges from as little as $68 per MWh in sunny locales like the Southwest or Texas to as much as $222 per MWh in less favorable locations such as New England.[13] Rooftop solar is even more expensive, usually double or triple the cost of utility-scale projects.[14]

Finally, even at today's historically low gas prices, existing reactors are cost-competitive with new natural gas-fired power plants, which range from roughly $52 to $77 per MWh.[15]

With few exceptions then, existing reactors should be considered a core component of an affordable low-carbon energy portfolio. Keeping existing reactors online represents a very cost-competitive alternative to building new wind or solar energy projects in all but the most remarkable locations.[16] And should gas prices rise in the future, preserving our nuclear fleet today will be viewed as an even wiser decision.

Rewarding the True Value of Nuclear

If maintaining existing nuclear units is so cost-effective, then why are they struggling?

Let's take a step back…as we've explained, maintaining an existing nuclear reactor is in most cases cheaper than replacing it with *new* resources. The problem is that some of these reactors find it difficult to compete in the short term with the *existing* resources on the grid, namely existing natural gas units that are driving wholesale prices lower due to cheap fuel.

The past twelve months have seen wholesale electricity prices across most of the United States drop to some of the lowest levels ever. And with overcapacity in many markets and slow growth for electricity demand, capacity market revenues, which compensate power plants for providing reliable power to meet peaks in electricity demand, have likewise plummeted. This creates a tough environment for all non-gas generators to survive in. Existing (and new) wind and solar units are able to compete because of external state and federal subsidies. Lacking a similar level of support, nuclear plants are being particularly hard-hit by the current market trend.

Surveying the range of wholesale and capacity market prices across the U.S. over the last 48 months, we estimate that while roughly half of the U.S. fleet is profitable,[17] the remainder of the fleet may be losing anywhere from a few dollars per MWh to as much as $21 per MWh considering ongoing refueling and O&M costs. Plants requiring major capital upgrades face higher losses, generally up to $31 per MWh, with a few of the most expensive plants facing losses as high as $42 per MWh (see Table 2).

Table 2. Estimated net income/loss/MWh of low-, medium-, and high-cost reactors with and without retrofit. *

Operations & Maintenance and Fuel Costs Only			
	LCOE	Net Income (High Revenues = $60.7)	Net Income (Low Revenues = $27.5)
Single reactor - low	$35.5	$25.1	-$8.0
Single reactor - medium	$45.2	$15.5	-$17.7
Single reactor - high	$48.9	$11.8	-$21.4
Dual reactor - low	$31.3	$29.4	-$3.8
Dual reactor - medium	$34.3	$26.4	-$6.8
Dual reactor - high	$47.5	$13.2	-$19.9
Costs Including Upgrades			
Single reactor - low	$44.2	$16.5	-$16.7
Single reactor - medium	$58.4	$2.2	-$30.9
Single reactor - high	$69.0	-$8.4	-$41.5
Dual reactor - low	$39.9	$20.7	-$12.4
Dual reactor - medium	$47.5	$13.1	-$20.0
Dual reactor - high	$67.6	-$6.9	-$40.1

**Estimates based on average market revenues from July 2012 to June 2016.*

As mentioned before, low electricity prices are clearly a boon for American consumers and industries. But these prices are rewarding low-cost generation in the short term, rather than supporting system-wide objectives like long-term affordability, fuel diversity, reliability, and emissions reduction. As a result, current electricity markets and policies are failing to fully value the contributions of the U.S. nuclear fleet.

Nuclear power plants deliver clean energy, free of any air pollutants and CO_2 emissions. The CO_2 emissions avoided by the nation's nuclear plants alone delivers an estimated public value of $6 to $54 per MWh.[18] The nation's nuclear fleet also helps avoid hundreds of thousands of tons of harmful air pollutants each year, including: particulate matter, which causes lung cancer, cardiovascular disease, and other devastating health impacts;

sulfur dioxide, which causes acid rain; nitrogen oxides, a precursor to smog; and toxic mercury, which can cause birth defects in children. Given these clean air benefits, it is not an exaggeration to say the U.S. nuclear fleet saves thousands of American lives each year.[19]

The nation's nuclear power plants are also an important component of a diverse and secure supply mix, providing a valuable hedge against volatility in natural gas prices. The value of fuel diversity is difficult to quantify, but if the nation's nuclear fleet was replaced by new natural gas plants, every $1 increase in the price per million Btus of natural gas would cost American consumers an extra $5.3 billion—or nearly $17 per person in the United States.[20]

In addition to fuel diversity benefits, nuclear contributes to overall grid stability. Nuclear reactors are built to run 24 hours a day every day of the year and only require refueling once every 18 to 24 months. This means that these units can continue to provide large amounts of electricity through periods of extreme heat or cold, coming to the rescue during events like the 'Polar Vortex' in January of 2014.[21]

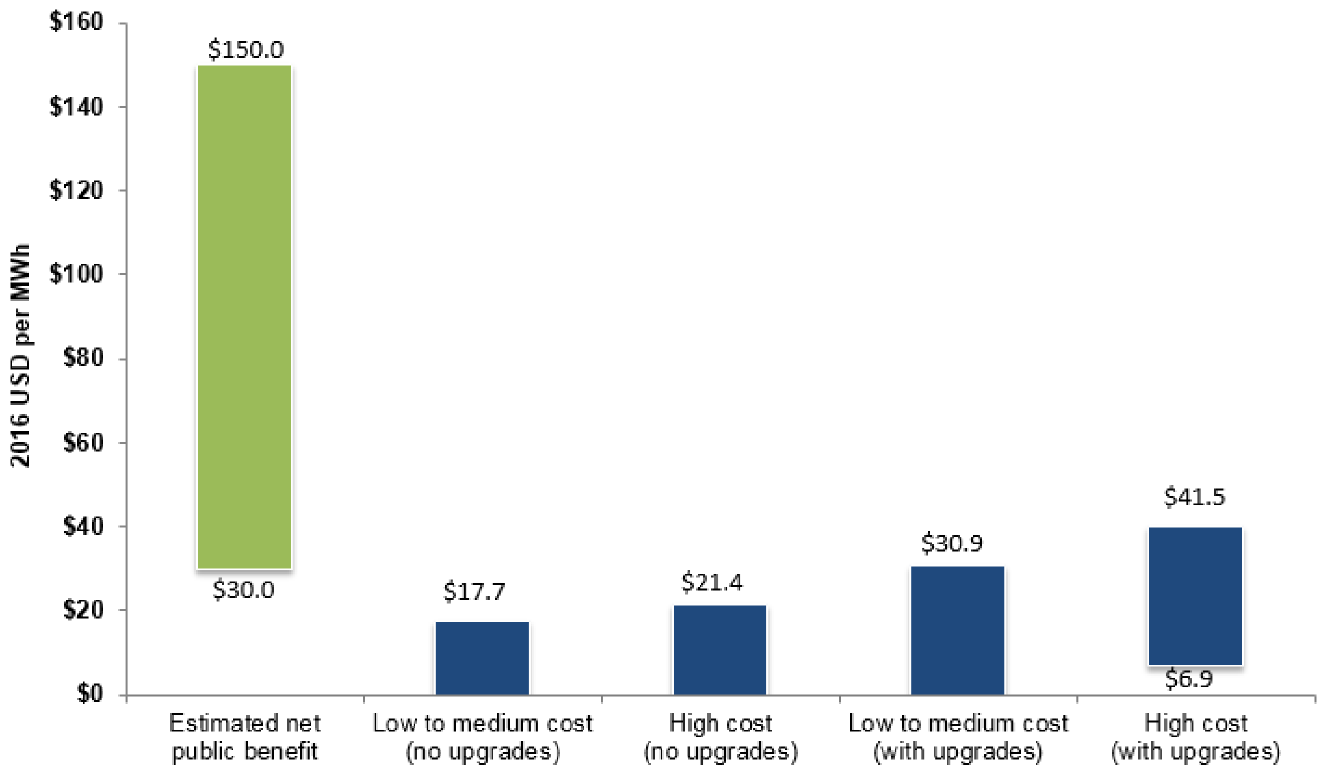
Renewable energy sources like wind and solar power deliver similar clean air and fuel diversity benefits as nuclear. Recognizing that these public benefits are not valued in electricity markets, a whole range of federal and state policies have been established to support renewable energy development—and with great success. Federal subsidies for wind and solar, including the production tax credit, investment tax credit, and accelerated depreciation, lower the effective LCOE of wind plants by $20 to $29 per MWh and by $26 to $85 per MWh for solar projects.[22] Wind and solar projects benefit further from state policies, particularly renewable portfolio standards (RPS), which require the adoption of a minimum amount of renewable energy and have been adopted in 29 states and the District of Columbia.[23] Renewable energy representing the value of renewable energy in meeting state RPS objectives have generally ranged from $10 to $65 per MWh.[24]

Public policy has recognized and monetized these valuable public benefits delivered by renewable energy—awarding renewable sources between $30 and $150 per MWh when state and federal incentives are combined. These subsidies have helped two important resources, wind and solar, to thrive during an economically challenging period for U.S.

power producers.

Nuclear power delivers the same benefits as renewable energy, including clean air, CO_2-free power, and increased fuel diversity, as well as the additional benefit of grid stability. Therefore, state and federal action to preserve America's nuclear fleet would be consistent with overall policy objectives and would deliver substantial net benefits to the public (see Figure 3).[25]

Figure 3. Estimated value of public benefits, such as clean air, avoided CO_2 emissions, and enhanced fuel diversity from existing nuclear compared to the value of policy support needed to keep existing reactors online.



New York is the first state to adopt a policy that rewards the low-carbon benefits of nuclear energy. The New York Public Service Commission recently approved a Clean Energy Standard which includes a zero emission energy credit for qualifying existing nuclear facilities. New York recognized that supporting the existing nuclear units is critical to meeting the state's emissions reduction goals – and to doing so more affordably. Reports have also shown that, by keeping these plants online, the State can avoid losing thousands of jobs in economically challenged areas and $720 million in tax revenue from these facilities.[26]

Illinois also recently passed legislation that values the climate benefits of existing nuclear units via zero emission credits. The Future Energy Jobs Bill will support the continued operation of two nuclear plants, Clinton and Quad Cities, which were slotted to retire in the next two years. These plants represent 23% of Illinois' clean electricity generation and the Illinois Environmental Protection Agency found that the retirement of the plants would produce an additional 21.5 million metric tons of CO_2 per year, resulting in over $10 billion in costs to society. The Illinois Department of Commerce and Economic Opportunity analyzed the impact of the nuclear plant retirements and found that the closure of the plants would result in the loss of 4,200 jobs and $1.2 billion in economic activity annually.[27] The passing of this bill will ensure that Illinois will continue to reap these environmental and economic benefits, while at the same time supporting the ongoing development of renewables and energy efficiency in the state.

These two states serve as a model demonstrating how policies can recognize the benefits of both renewables and nuclear, and their approach should be considered by other states with nuclear units at risk.

Policies to Preserve America's Clean Energy Foundation

A variety of federal and state policy actions could help close the gap between the cost of existing nuclear plants and their expected revenues in electricity markets. To save all reactors not requiring upgrades, a combination of state and federal policies would need to provide financial support in the range of $4 to $21 per MWh. Increasing policy assistance up to $31 per MWh could save all but the most expensive plants requiring upgrades.

The federal government has an important leadership role to play in preserving the existing nuclear fleet, given the national interest in meeting climate change goals, maintaining a secure and reliable energy system, and a vibrant economy with a highly skilled workforce. The states also have a critical role to play as they are well positioned to implement solutions that are tailored to the circumstances of each region. In particular, states could expand state renewable portfolio standards to include nuclear generation or provide tax credits to nuclear units. The National Conference of State Legislatures offers a number of additional state level actions to retain nuclear facilities.[28]

In this paper, we have chosen to focus on federal policy options for properly rewarding the value of existing nuclear power plants. The costs associated with these recommended actions would be significantly less than the total public benefits delivered and compare favorably to existing policy support for other sources of clean energy. The federal policies alone are unlikely to save all at-risk nuclear plants, so parallel state initiatives will still be needed in many instances to keep these valuable resources operating.

Federal Tax Incentives

An immediate solution would be to expand the production tax credit (PTC) of $18/MWh for new nuclear plants to include existing units. PTCs are generally intended as a mechanism to help new market entrants overcome economic hurdles, but a case could be made that these existing nuclear facilities face significant expenditures to remain operational, and their closure could threaten the country's shift towards a clean generation mix.[29] A more significant obstacle for this policy would come from its price tag—roughly $14 billion to support 800,000 GWh of generation annually if provided to all units. Despite this large price tag, it should be noted that the public benefits of maintaining these plants—on the order of $24 to 120 billion annually—far outweigh the cost.

An investment tax credit (ITC) on new investments in capital upgrades or nuclear fuel assemblies coupled with an accelerated depreciation incentive is another option. An ITC with accelerated depreciation could reduce existing facilities' tax burden, thereby slightly reducing costs and closing the gap to profitability. We estimate that a 30% ITC with accelerated depreciation for existing nuclear facilities could reduce the levelized cost of plants by $3.3 per MWh for fuel expenditures and by another $3.5-8.2 per MWh for plants facing capital upgrades or retrofits. Although the size of the incentive may only be helpful for the most efficient plants, the impact of this federal policy could be more far-reaching if coupled with state incentives.

Adjustments to Federal Power Market Regulations

The Federal Energy Regulatory Commission (FERC) oversees the regional power markets that operate throughout the United States. FERC has recently initiated action addressing a number of issues to improve how wholesale prices are set and to reward reliability in electricity markets. Although progress has been made, further steps could be taken to establish markets in all regions that ensure that resources are compensated for meeting reliability requirements.

In addition, FERC is required to review and approve any changes proposed by Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) to their market structure. FERC also decides on cases in which one or more parties believe that a proposed action may interfere with market rules. FERC should work to accommodate actions taken by states and RTOs/ISOs that attempt to introduce appropriate, market-friendly mechanisms to support clean energy resources, particularly reliability enhancing baseload options.[30]

In the longer term, it is worthwhile to conduct a broader review of the electricity markets to assess their overall performance in terms of market efficiency, securing system reliability, and maintaining critical low-carbon power. This will be a long and complex process, but is necessary to begin moving towards a market system that inherently values the attributes that are critical to achieve a clean, reliable, and secure electricity system.

National Clean Energy Standard

A nation-wide clean energy standard (CES) would mandate that clean energy, including nuclear, provide a significant and growing percentage of America's total electricity consumption. Mandating a certain amount of clean electricity would indirectly increase the value of nuclear energy by increasing demand for all low-carbon sources. This is something that has previously been proposed by President Obama and debated in Congress. The potential clean energy benefits of a national CES would be huge—and so would the political challenge of getting it enacted.

Putting a Price on Carbon

The general consensus among economists is that the most efficient way to support low-carbon technologies is by putting a price on carbon. Putting a price on carbon could make existing nuclear (and renewables) more competitive, as it would require fossil fuel generators to include the cost of carbon emissions in their electricity prices. We estimate that a carbon price of roughly $42 per ton of CO_2—what the EPA has determined to be the "social cost of carbon"—would be sufficient to help all but the highest cost reactors requiring retrofits.[31] While a price on carbon has the potential to be a very effective tool, there is currently not sufficient political support for a carbon tax at the federal level.

Conclusion

Our existing nuclear fleet is the foundation on which clean energy progress can be built. If this foundation crumbles, so too will our national energy security, climate, and clean energy goals—taking thousands of jobs and substantial economic benefits with it.

Fortunately, preserving existing reactors remains one of the most cost-effective ways for America to produce clean electricity and pave the way for a more secure, lower-carbon electricity system. Maintaining existing nuclear units is more cost-effective in most cases than building new low-carbon resources. And the value of the public benefits, including the low-carbon and fuel diversity attributes, far outweighs the cost of the policy supports that are needed to keep these units in operation.

Endnotes

1. United States, Energy Information Administration, “Table 12.6. Carbon Dioxide Emissions From Energy Consumption: Electric Power Sector,” August 2016. Accessed October 27, 2016. Available at: http://www.eia.gov/totalenergy/data/monthly/pdf/sec12_9.pdf.

2. United States, Nuclear Regulatory Commission, “Backgrounder on Decommissioning Nuclear Power Plants”, May 2015. Accessed October 27, 2016. Available at: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/decommissioning.html.

3. Nuclear Energy Institute, Accessed on: December 2, 2016. “Why Nuclear Energy: Economic Growth & Job Creation”. Available at: http://www.nei.org/Why-Nuclear-Energy/Economic-Growth-Job-Creation

4. Bloomberg New Energy Finance, “Reactors in the red: financial health of the US nuclear fleet”, July 2016.

5. United States, Energy Information Administration, “Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2006-June 2016”, June 2016. Accessed October 27, 2016. Available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01. and United States, Energy Information Administration, “Table 1.1.A. Net Generation from Renewable Sources: Total (All Sectors), 2006-June 2016”, June 2016. Accessed October 27, 2016. Available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01_a.

6. Sam Brinton and Josh Freed, “When Nuclear Ends: How Nuclear Retirements Might Undermine Clean Power Plan Progress”, Third Way, August 2015. Accessed October 27, 2016. Available at: http://www.thirdway.org/report/when-nuclear-ends-how-nuclear-retirements-might-undermine-clean-power-plan-progress.

7. Calculations assume 55 percent of annual U.S. nuclear electricity generation, or 438.5 million MWhs, is lost and replaced by new natural gas combined cycle power plants with a heat rate of 6.69 million Btus per MWh consuming natural gas with 117 pounds of CO2 per million Btus.

8. United States, Environmental Protection Agency, “Greenhouse Gas Equivalencies Calculator”. Accessed October 27, 2016. Available at: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

9. Nuclear costs are estimated based on available government and industry data as follows:
Fixed operation and maintenance, fuel, and variable operating costs reflect the range of figures reported in the following three sources:
(1) Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, and Illinois Department of Commerce and Economic Opportunity, “Potential Nuclear Power Plant Closures in Illinois: Impacts and Market-Based Solutions,” January, 2015.
(2) Nuclear Energy Institute, “Nuclear Energy 2016: Status and Outlook. Annual Briefing for the Financial Community,” February 11, 2016.
(3) Nuclear Energy Institute, “Nuclear Costs in Context,” April 2016.
For single unit reactors, the low and high cost estimates reflect the lowest and highest reported costs from Illinois Commerce Commission et al., while the middle cost estimate reflects average cost for single unit U.S. reactors reported by NEI. For dual unit reactors, the low cost estimate reflects 1st quartile U.S. reactor costs reported by NEI, the middle estimate reflects average cost for dual unit U.S. reactors reported by NEI, and the high cost reflects the highest reported costs from Illinois Commerce Commission et al.
We assume capacity factors of 89, 93 and 95 percent for the high, medium, and low cost estimates, respectively, reflecting the 1st quartile, median, and 3rd quartile of reported capacity factors across the U.S. nuclear fleet from 2013-2015, from United States, Energy Information Administration, “U.S. Nuclear Generation and Generating Capacity”, Accessed October 27, 2016. Available at: https://www.eia.gov/nuclear/generation/.
See endnote 10 for details on levelized cost of electricity calculation.
Note that these cost estimates are designed to span the large majority of costs for U.S. reactors. Some outliers may exist, including particularly high performing plants with costs below our lowest estimate and poor performing plants experiencing frequent outages and reduced capacity factors exhibiting costs above the our highest cost estimate.

10. For individual technology cost assumptions, see endnotes 9, 11, 12, 13, and 15. Capital costs for all technologies assume 12 percent cost of equity and 8 percent cost of debt with 40 percent equity share, 20 year asset life for nuclear

retrofits and 30 year asset life for solar, wind, and natural gas plants. All projects assumed to have 40 percent combined state and federal marginal business tax rate and 20 year straight-line asset depreciation schedule. All reported cost values used in this analysis are converted to 2016 USD using the Bureau of Labor Statistics Consumer Price Index Inflation Calculator.
Levelized cost of electricity formula from United States, National Renewable Energy Laboratory,"2016 Annual Technology Baseline", Accessed October 27, 2016. Available at: http://www.nrel.gov/analysis/data_tech_baseline.html.

11. Capital retrofit costs from International Energy Agency and Nuclear Energy Agency, "Projected Costs of Generating Electricity: 2015 Edition", August, 2015. Accessed October 27, 2016. Available at: https://www.iea.org/Textbase/npsum/ElecCost2015SUM.pdf. Costs reflect the lowest, average, and highest cost estimates reported for six OECD countries, and range from $544 to $1,185 USD per kilowatt (2016 dollars). See endnote 10 for details on levelized cost of electricity calculation.

12. Wind cost inputs represent the lowest and highest estimates from both Lazard (see endnote 14) and NREL (see endnote 15). Capacity factors for wind assumed to be 30, 43, and 50 percent for our high, medium, and low cost estimates, respectively. See endnote 10 for details on levelized cost of electricity calculation. Note that these estimates are for land-based wind farms. Offshore wind farms remain much more costly at this point. The nations' first offshore wind farm, the Block Island project scheduled to go online later this year off the shores of Rhode Island, will cost $244 per MWh, and that is *after* discounts reflecting the value of federal and state tax incentives. See Alex Kuffner,"Opponents File Challenge to Block Island Wind Farm in Federal Court", Providence Journal, August 17, 2015. Accessed October 27, 2016. Available at http://www.providencejournal.com/article/20150817/NEWS/150819383.

13. Solar cost inputs represent the lowest and highest estimates from both Lazard (see endnote 14) and NREL (see endnote 15). Capacity factors for solar are assumed to be 14, 23, and 32 percent for our high, medium, and low cost estimates, respectively. See endnote 10 for details on levelized cost of electricity calculation.

14. Lazard, "Lazard's Levelized Cost of Energy Analysis: Version 9.0", November, 2015. Accessed October 27, 2016. Available at: https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-90/.

15. Natural gas combined cycle cost inputs from United States, National Renewable Energy Laboratory (NREL), "2016 Annual Technology Baseline", April 2016. Accessed October 27, 2016. Available at: http://www.nrel.gov/analysis/data_tech_baseline.html. Capacity factors assumed to be 40, 60, and 80 percent for high, medium, and low cost estimates, respectively. See endnote 10 for details on levelized cost of electricity calculation.

16. These conclusions become even more apparent when we consider that nuclear power plants provide reliable electricity 24-7, whereas wind and solar power output fluctuates with the strength of the wind and the sun. Comparing the costs of different resources is thus only half the equation. The value of each MWh of electricity generated by each resource must be considered as well. A range of researchers have concluded that the value of wind and solar energy both decline as these resources increase in market share. For example, the more solar energy that feeds into the grid, the lower the wholesale price will be during periods of peak solar production. At high market shares, wind and solar output might have to be curtailed or wasted during certain hours in order to maintain enough dispatchable generation online to keep power systems reliable. Finally, integrating more and more wind and solar power requires grid operators to commit more "reserves" or standby capacity from dispatchable generators capable of stepping in if the wind or sun unexpectedly falter, which further reduces the relative value of these intermittent resources. For more information on the value of intermittent resources, see: Alan Lamont, "Assessing the Long-term System Value of Intermittent Electric Generation Technologies", *Energy Economics,* 30: 1208-1231. United States, Lawrence Berkeley National Laboratory, "Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California", June 2012. Lion Hirth, "The Market Value of Variable Renewables: The Effect of Solar and Wind Power Variability on their Relative Price", July 2013, *Energy Economics,* 38: 218-236. United States, Lawrence Berkeley National Laboratory, "Strategies for Mitigating the Reduction in Economic Value of Variable Generation with Increasing Penetration Levels", March 2014. Electric Power Research Institute, "Program 178b: Decreasing Returns to Renewable Energy", EPRI Technical Update Product #3002003946, January 2015. Lion Hirth, "The Optimal Share of Variable Renewables: How the Variability of Wind and Solar Power Affects their Welfare- Optimal Deployment", November 8, 2013, *The Energy Journal* 36(1): 127-162. Lion Hirth, Falco Ueckerdt, and Ottmar Edenhofer, "Integration Costs Revisited: An Economic Framework for Wind and Solar Variability", *Renewable Energy* 74: 925-939. United States, National Renewable Energy Laboratory and Department of Energy, "On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System", May 2016.

17. Profit and loss estimates based on range of average wholesale electricity prices for 48 months from July 2012 to

June 2016 (inclusive) for hubs in ISO New England, New York ISO, PJM, Midwest ISO, Electricity Reliability Corporation of Texas (ERCOT), and California ISO marketplaces based on publicly available data published by each market operator. Prices for New York ISO zones B, C and I are used, as these zones are home to the state's nuclear reactors. Capacity market revenues from the latest capacity auction in New England ISO, PJM, New York ISO, and Midwest ISO also included in estimated revenues for these regions. 48-month average revenues range from $27.5 to $60.7 per MWh, and these revenues are compared to the range of estimated levelized cost of electricity for existing nuclear plants, as per endnote 10 above.

18. Estimated value of avoided CO2 emissions ranges from $12.77 to $65.00 per metric ton of CO2 in 2016 USD, based on social cost of CO2 from U.S. EPA (2015). EPA Fact Sheet: Social Cost of Carbon. U.S. Environmental Protection Agency, December 2015. Reported average social cost of CO2 for 2015 using 2.5, 3 and 5 percent discount rates inflated to 2016 USD using the Bureau of Labor Statistics Consumer Price Index Inflation Calculator. Public benefit per MWh of nuclear generation estimated using regional average marginal emissions rates ranging from 0.486 to 0.834 tons CO2 per MWh, as reported by Kyle Siler-Evans, Ines Azevedo, and M. Morgan, "Marginal Emissions Factors for the U.S. Electricity System", *Environmental Science and Technology,* 46(9): 4742–4748.

19. A 2010 report estimated that particulate emissions from U.S. plants alone are responsible for 7,500 deaths annually. Clean Air Task Force, "The Toll from Coal: An Updated Assessment of Death and Disease from America's Dirtiest Energy Source", September 2010. Accessed October 27, 2016. Available at: http://www.catf.us/resources/publications/view/138.

20. Estimate assumes total U.S. nuclear generation of 797 million MWhs (EIA, 2016b) replaced by combined cycle gas plants with a heat rate of 6.69 million Btus (MMBtus) per MWh (NREL, 2016). Total increased gas consumption is thus 5.3 billion MMBtus, yielding $5.3 billion increase per dollar increase in gas price per MMBtu. U.S. population in 2014 was 319 million, for a total cost per person of $16.60.

21. Nuclear Matters, "Fact Sheet 3. Nuclear Benefits: Always-on Reliability", March 2014. Accessed October 27, 2016. Available at: http://www.nuclearmatters.com/resources/fact-sheets/document/3-Nuclear-Matters-Reliable-Power.pdf.

22. Author's estimates using levelized cost of electricity formula from NREL (see endnote 15). Federal ITC reduces overnight capital cost by 30 percent, lowering the levelized cost of solar projects by roughly $19 to $63 per MWh given LCOE assumptions described in endnote 10. Production tax credit delivers $23 per MWh (rising with inflation) for the first ten years of the project, reducing the levelized cost of electricity from wind projects by $14.76 per MWh. Benefits of a five-year modified accelerated depreciation schedule (MACRS) are compared to a 20-year straight-line depreciation schedule, resulting in a reduction in levelized cost ranging from roughly $5 to $14 per MWh for wind and $7 to $22 per MWh for solar projects, depending on capital cost assumptions.

23. North Carolina State University and U.S. Department of Energy, "Database of State Incentives for Renewable Energy," August 2016. Accessed October 27, 2016. Available at: http://www.dsireusa.org/.

24. United States, National Renewable Energy Laboratory, "A Survey of State-Level Cost and Benefit Estimates of Renewable Portfolio Standards," Technical Report, May 2014. Accessed October 27, 2016. Available at: http://www.nrel.gov/docs/fy14osti/61042.pdf. Note that set-asides or carve-out provisions for solar in some states have valued solar at as much as $100 to $500 per MWh.

25. Estimated value of public benefits derived from current level of policy support for renewable resources providing comparable clean air, avoided CO2 and enhanced fuel diversity benefits.

26. Mark Berkman and Dean Murphy, "New York's Upstate Nuclear Power Plants' Contribution to the State Economy," Brattle Group, December 2015. Accessed December 2, 2016. Available at: http://www.brattle.com/system/news/pdfs/000/000/969/original/New_York's_Upstate_Nuclear_Power_Plants'_Contribution_to_the_State_Economy.pdf?1449526627.

27. Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, and Illinois Department of Commerce and Economic Opportunity, "Potential Nuclear Power Plant Closures in Illinois: Impacts and Market-Based Solutions," January, 2015. Accessed on December 2, 2016. Available at: http://www.ilga.gov/reports/special/Report_Potential%20Nuclear%20Power%20Plant%20Closings%20in%20IL.pdf.

28. National Council of State Legislatures, "State Action in Support of Nuclear Generation", August 29, 2016. Accessed October 27, 2016. Available at: http://www.ncsl.org/research/energy/state-action-in-support-of-nuclear-

generation.aspx.

29. Susan Tierney, Remarks, U.S. Department of Energy Summit on Improving the Economics of America's Nuclear Power Plants, May 19, 2016, Washington, D.C.

30. In addition, ISO NE stakeholders are currently evaluating a carbon pricing mechanism for their regional energy markets. If this proposal moves forward, it may require FERC review and approval.

31. Note that a price on carbon would not act as a direct subsidy to nuclear. A price on carbon would increase the cost of fossil-fired sources, thereby driving wholesale prices higher, and as a result, increase the revenues of nuclear.