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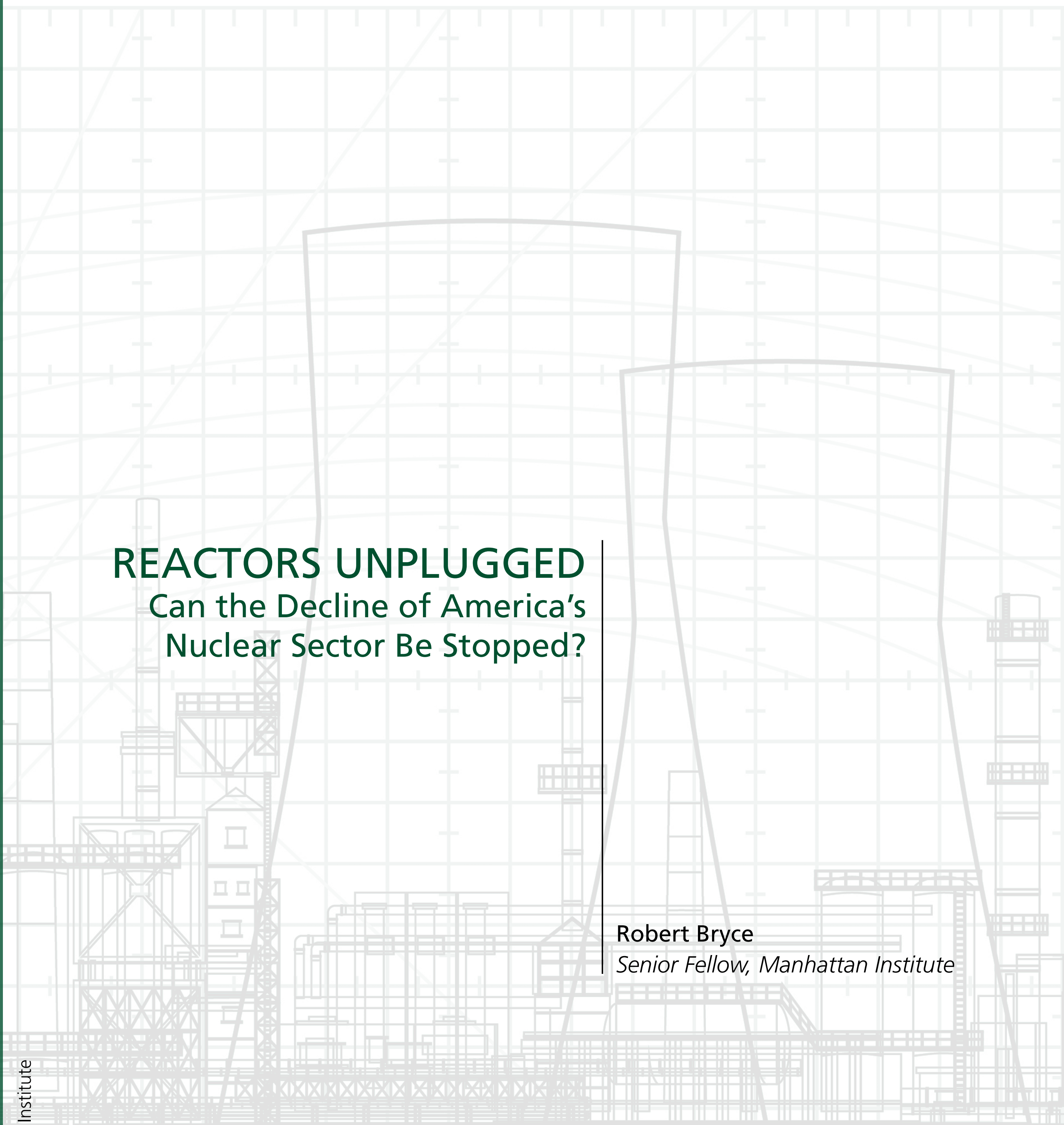

REACTORS UNPLUGGED
Can the Decline of America's Nuclear Sector Be Stopped?

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Executive Summary

Today, the United States has 99 nuclear reactors that provide about 20 percent of the country's electricity.[1] Globally, nuclear reactors provide about 11 percent of the world's electricity.[2] That global fleet of reactors is also helping avoid the release of about 2.5 billion tons of carbon dioxide annually. But nuclear energy has long been controversial because of concerns about safety and waste disposal. Despite such concerns, many politicians, environmentalists, and climate-change activists are embracing nuclear energy as an irreplaceable component in the effort to reduce the rate of growth in global carbon-dioxide emissions.

This paper examines current trends in U.S. nuclear power, the factors hampering nuclear's revival, and the steps that could be taken by the federal government to facilitate the growth of America's nuclear-energy sector. Key findings include:

1. After decades of growth, U.S. nuclear output has flattened and is now facing the possibility of significant decline. Over the next half-decade, about 10 gigawatts of U.S. nuclear capacity may be shut down because of economic and regulatory pressures. (A gigawatt of nuclear capacity can provide baseload power to about 750,000 homes.)[3]
2. That 10 gigawatts of nuclear capacity represents about 6 percent of U.S. low-carbon electricity production.
3. Matching the low-carbon electricity output from 10 gigawatts of nuclear capacity with solar would require installing twice as much solar capacity as now exists in Germany, a country that produces about one-fifth of the world's solar electricity.
4. Matching the low-carbon electricity output from 10 gigawatts of nuclear capacity with wind would require installing 1.5 times as much wind capacity as now exists in Spain.
5. The decline of U.S. nuclear is due to a number of factors, including the high cost of new reactors, the low price of natural gas, subsidized renewable energy that distorts pricing in the wholesale electricity market, and the increasing regulatory burden on existing reactors.
6. If America wants to remain a significant player in nuclear energy and, therefore, in low-carbon electricity production, it will have to solve the issue of nuclear waste. It will also have to facilitate the research and development of new reactor designs and streamline the process for permitting and siting those new reactors.

About the Author

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Bryce has delivered more than 200 invited and keynote lectures to groups of all kinds, ranging from the Marine Corps War College and University of Calgary, to the Sydney Institute and Melbourne's Institute of Public Affairs. He appears regularly on major media outlets, including CNN, Fox News, PBS, NPR, and BBC. Bryce holds a B.F.A. from the University of Texas at Austin.

CONTENTS

1 Introduction

3 I. Nuclear's Role in Carbon-Free Electricity Production

4 II. America's Faltering Nuclear Sector

6 III. Implications of the Loss of U.S. Nuclear Capacity

8 IV. Factors Driving the Decline

14 V. The Case for Nuclear

15 VI. Encouraging a New Generation of Nuclear

17 Conclusion

19 Appendix A

19 Appendix B

21 Endnotes

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INTRODUCTION

Of all the methods that humans use to produce energy, our ability to harness the power of the atom is among the newest (**Figure 1**). Coal has been in use for millennia and has been in common industrial use for about 300 years. Similarly, the history of oil goes back centuries. The adventurer Marco Polo reported seeing oil, collected from seeps near Baku, used for medicinal purposes as well as for lighting.[4] By the 1500s, oil was being used to light streetlamps in Poland.[5] The history of natural gas is somewhat shorter, but the fuel was being used to provide lighting for the courthouse in Stockton, California, in 1854.[6]

Renewable energy also has a long history. Humans and their ancestors have been burning wood since the use of fire became common among hominins more than 300,000 years ago.[10] Windmills have been in use for more than 1,000 years.[11] The photovoltaic effect was first observed in 1839, and the first solar-photovoltaic device was introduced by Bell Labs in 1954.[12]

Meanwhile, the world's first commercial nuclear plant was Calder Hall, which began producing electricity in Britain in 1956.[13] A year later, the first commercial reactor in the U.S. began operating at Shippingport, Pennsylvania.[14] More than 400 nuclear reactors are now operating around the world.[15] But the technology used to generate electricity from nuclear reactors has not changed much since the 1950s and 1960s. About 80 percent of all reactors now producing electricity use just two designs: pressurized water or boiling water. While those designs have proved durable, they have remained essentially unchanged for decades.

Today, America's nuclear industry stands at a crossroads. The industry is increasingly reliant on plants that are facing retirement due to age, economic considerations, or both. The average U.S. nuclear reactor is about 34 years old.[16] While that is certainly far older than the average U.S. natural gas–fired power plant—which has an average age of about 12 years[17]—modern nuclear reactors likely have useful life spans of 60 or even 80 years.[18]

Although five reactors are now being built in the U.S., the number of nuclear-generation plants that could be retired over the next decade or so far exceeds that number. The EPA's much-ballyhooed Clean Power Plan, which aims to reduce greenhouse gas emissions from the electric sector, does not include policies that will help keep existing nuclear reactors in operation. Indeed, barring significant government intervention, the decline of America's nuclear sector may be inevitable.

Figure I. Nuclear Energy: A Timeline

1942:	The first self-sustaining nuclear chain reaction occurs at the University of Chicago.
1945 (July 16):	The U.S. military tests the first atomic bomb at Alamogordo, New Mexico, under the code name Manhattan Project.
1945 (August 6):	The atomic bomb is dropped on Hiroshima, Japan. Three days later, another bomb is dropped on Nagasaki.
1946:	Congress creates the Atomic Energy Commission to control nuclear-energy development and explore peaceful uses of nuclear energy.
1951:	The first electric power is produced from nuclear energy in Arco, Idaho. The electricity is used to power four lightbulbs.
1953:	President Dwight Eisenhower delivers his Atoms for Peace speech before the United Nations.
1957:	The Price-Anderson Act provides financial protection to the public, as well as to companies that own and operate nuclear reactors, in case of a major accident.
1957:	The first large-scale nuclear power plant in the U.S. begins operating at Shippingport, Pennsylvania.
1971:	Nuclear energy provides 2.4 percent of U.S. electricity from 22 commercial nuclear reactors.
1973:	U.S. utilities order 41 nuclear reactors, a record for a single year.
1977:	President Jimmy Carter announces that the U.S. will quit reprocessing spent nuclear fuel.
1979:	The Three Mile Island nuclear plant in Pennsylvania sustains the worst nuclear accident in U.S. history.
1979:	Nuclear's share of U.S. electricity generation reaches 12 percent with 72 licensed reactors.
1983:	Congress passes the Nuclear Waste Policy Act, which creates a program to site a repository for the disposal of high-level radioactive waste, including spent fuel from nuclear reactors.
1984:	Nuclear-energy production exceeds hydropower to become the second-largest source of electricity, after coal. Reactors provide 14 percent of U.S. electricity from 83 reactors.
1986:	Major accident at the Chernobyl facility in Ukraine, leading to the largest uncontrolled release of radioactive materials into the environment by a civilian operation.[7]
1989:	Reactors provide 19 percent of U.S. electricity from 109 reactors.
1992:	Nuclear's share of the U.S. electricity market reaches nearly 22 percent.[8]
2011:	Three reactors at Japan's Fukushima Daiichi plant melt after they are hit by a massive earthquake and a series of seven tsunamis.
2015:	Construction on Watts Bar Unit 2, a nuclear reactor owned by the Tennessee Valley Authority, is slated to be completed, 42 years after it was begun.[9]

I. NUCLEAR'S ROLE IN CARBON-FREE ELECTRICITY PRODUCTION

While nuclear reactors provide about 20 percent of America's electricity, they also provide more than 60 percent of the country's low-carbon electricity. In 2013, nuclear provided nearly three times as much low-carbon electricity to the U.S. economy as did hydropower, the next-largest source of carbon-free electricity.

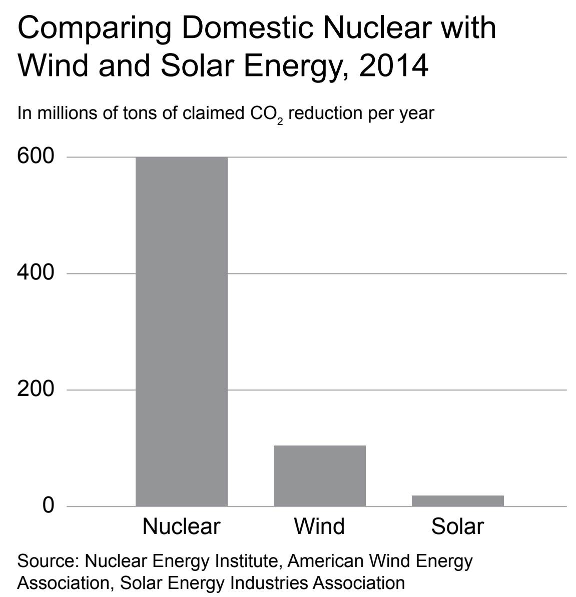
Those reactors help control carbon-dioxide emissions. In 2014, nuclear energy avoided about 600 million tons of carbon-dioxide emissions in the U.S. (**Figure 2**).[19] That is equal to about 10 percent of total U.S. emissions;[20] to about six times the emissions reductions claimed by America's wind-energy sector;[21] and to 23 times the amount claimed by America's solar-energy sector.[22]

These figures demonstrate that nuclear's ability to reduce carbon dioxide is far greater than what has been achieved with wind and solar energy. The avoided emissions now being obtained with U.S. nuclear are equal to about 75 percent of the emission cuts that are projected to occur under the Obama administration's Clean Power Plan, which aims to cut annual carbon-dioxide emissions from electricity generation by about 800 million tons by 2030.[23] Shortly after the final version of the rule of the Environmental Protection Agency (EPA) was released, one analyst concluded that if "more than just a handful of nuclear power plants retire by 2030, it could sabotage the carbon reductions targeted" by the Clean Power Plan.[24]

Globally, nuclear energy plays an important role in providing low carbon electricity. Today, some 31 countries produce electricity from 435 commercial nuclear reactors.[25] Global nuclear capacity totals about 375 gigawatts and helps avoid about 2.5 billion tons of carbon-dioxide emissions annually, or about 7 percent of global emissions.[26]

In addition to its ability to avoid carbon-dioxide emissions, nuclear reactors provide baseload electricity (power that is continuously available).

Figure 2. Avoiding Carbon-Dioxide Emissions: U.S. Nuclear, Wind, and Solar Energy, 2014



Source: Nuclear Energy Institute, American Wind Energy Association, Solar Energy Industries Association

Baseload power is a critical factor in maintaining the reliability of the electric grid. That attribute stands in stark contrast to the intermittent electricity produced by renewable sources, such as solar and wind. Indeed, intermittency is a key problem for wind energy because the production of electricity from wind turbines often peaks at night, when electricity demand is lowest. In big wind-energy states such as Texas, wind output regularly falls to its lowest levels when demand is highest.[27]

Nuclear's carbon-dioxide and land-use advantages have attracted vocal support from politicians, energy analysts, and climate-change activists. For instance, in 2011, Ernest Moniz penned a long article for *Foreign Affairs*, titled "Why We Still Need Nuclear Power." Moniz, who was then leading the Energy Initiative at MIT and now heads the U.S. Department of Energy (DOE), outlined the challenges facing the nuclear sector, before concluding: "A more productive approach to developing nuclear power—and confronting the mounting risks of climate change—is long overdue."[28]

Or consider the pronuclear stand of Stewart Brand, the prominent environmentalist who gained fame as the publisher of the *Whole Earth Catalog*, a book that helped define the 1960s and 1970s in America. In a trailer for the recent documentary *Pandora's Promise*, Brand said: "The question is often asked, 'Can you be an environmentalist and be pronuclear?' I would turn that around and say: 'In light of climate change, can you be an environmentalist and not be pronuclear?' "

In a 2012 article in *Foreign Policy*, "Out of the Nuclear Closet: Why It's Time for Environmentalists to Stop Worrying and Love the Atom," Michael Shellenberger, along with his Breakthrough Institute cofounder, Ted Nordhaus, and colleague Jessica Lovering, summed up the position of the pronuclear Left: "Climate change—and, for that matter, the enormous present-day health risks associated with burning coal, oil, and gas—simply dwarfs any legitimate risk associated with the operation of nuclear power plants."[29]

In late 2013, one of the world's most prominent climate scientists, James Hansen, along with three other climate scientists, wrote an open letter to environmentalists, encouraging them to support nuclear. "Continued opposition to nuclear power threatens humanity's ability to avoid dangerous climate change," they declared. "[Renewable sources] like wind and solar and biomass will certainly play roles in a future energy economy, but those sources cannot scale up fast enough to deliver cheap and reliable power at the scale the global economy requires."[30]

Given nuclear's many advantages over renewable-energy forms such as solar and wind, as well as its obvious strength in cutting carbon-dioxide emissions, America should be in the midst of a nuclear renaissance. However, that is not the case.

II. AMERICA'S FALTERING NUCLEAR SECTOR

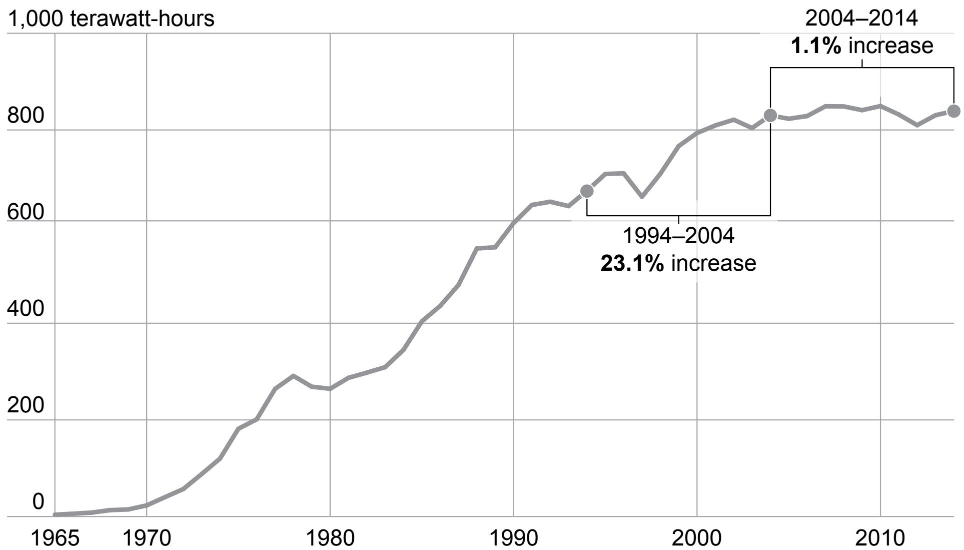
When it comes to nuclear-energy production, the U.S. currently has a substantial lead over the rest of the world. In 2014, America produced about one-third of the world's nuclear power, nearly 800 terawatt-hours. That volume of electricity was about twice as much nuclear energy as was produced by France.[31] But domestic production of electricity from nuclear reactors has plateaued and has been effectively flat for the last decade. Between 2004 and 2014, output from U.S. reactors increased by just 1.1 percent (**Figure 3**). By contrast, from 1994 to 2004, output from U.S. reactors increased by 23.1 percent.

Five reactors are now being built in the United States. But that new capacity is a small fraction of what is being built in other countries (**Figure 4**). China is building 23 reactors. Russia has nine reactors under construction, and India has six. After those five reactors are completed in the U.S., only one small electric-power reactor (with an output of about 50 megawatts) is being actively planned. In May 2015, DTE Energy announced that it had received a license from the U.S. Nuclear Regulatory Commission (NRC) to build and operate a new 1,560-megawatt reactor, Fermi 3, next to its Fermi 2 nuclear plant on Lake Erie. But DTE stressed that it has no plans to actually build the new reactor and that it sought the license from the NRC as a long-term planning option.[32]

In the past two years, utilities have shuttered 4.2 gigawatts of nuclear-generating capacity. Closures include the San Onofre Nuclear Generating Station (2,250 MW),[33] Crystal River 3 Nuclear Power Plant (860 MW),[34] Kewaunee Power Station (556 MW),[35] and Vermont Yankee (620 MW).[36] In each case, owners of the reactors said that the closures were due to the high costs of operating the plants. For instance, the Vermont Yankee facility had a license to operate until 2032, but the plant's owner, Entergy Corporation, chose to shut it for economic reasons.[37]

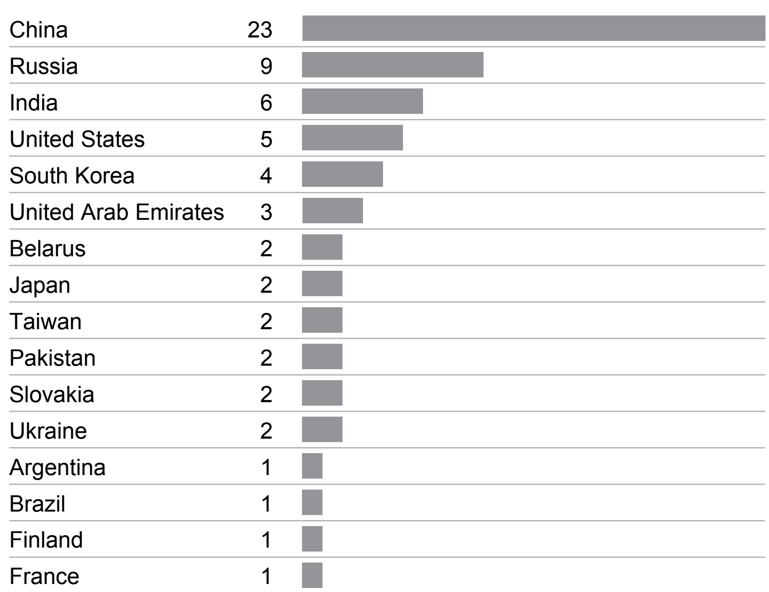
Other nuclear utilities are also choosing to shutter their reactors ahead of schedule. Exelon Corporation, the biggest producer of nuclear energy in the U.S. and the third-largest nuclear producer in the world, announced that it will close its Oyster Creek

Figure 3. U.S. Nuclear-Energy Production, 1965–2014



Source: BP Statistical Review of World Energy 2015

Figure 4. Nuclear Reactors Under Construction, 2015



Source: International Atomic Energy Agency plant in 2019, a decade sooner than planned.[38] At another Exelon plant, the Ginna Nuclear Generating Plant, the company is seeking subsidies from ratepayers to keep the reactor operating.[39]

At least nine domestic nuclear plants are struggling to stay open because of poor economics (**Figure 5**). In August 2015, the EPA released the final draft of the Clean Power Plan, the federal rules that aim to cut carbon-dioxide emissions from the electricity-generation sector. While the plan does provide incentives for nuclear reactors that are now being built, as well as for reactors that may be built in the future, it does not give proper credit to existing nuclear plants and their value in helping reduce emissions.[40]

The sum of the capacity listed in Figure 5 reveals that about 10.5 gigawatts of America's nuclear capacity is facing shutdown.[45] Thus, over the course of this decade, the U.S. could see the closure of about 14.7 gigawatts of domestic nuclear capacity while bringing online about 5.5 gigawatts—a net loss of 9.2 gigawatts of nuclear capacity, or nearly 10 percent of U.S. nuclear capacity.[46]

But this projection may understate possible closures. In 2013, the Center for Strategic and International Security released a report predicting that as many as 25 of America's 99 commercial reactors could be shuttered by 2020.[47] The report added that "with uncertainty about the prospects for new plant construction over the next decade and with nearly all existing plants scheduled to be shut down by 2050, the share of electricity generated by nuclear reactors in the United States will decline steadily to near zero by mid-century."[48]

III. IMPLICATIONS OF THE LOSS OF U.S. NUCLEAR CAPACITY

While it is not yet clear how much U.S. nuclear capacity will be retired in the next one or two decades, each 10 gigawatts of nuclear capacity that is lost will result in the loss of about 75 terawatt-hours of low-carbon electricity production annually.[49] That amounts to about 6 percent of America's low-carbon electricity output.[50]

Figure 5. U.S. Nuclear Plants Facing Closure

1.	Indian Point 2 & 3, New York (2,060 MW)
2.	Fitzpatrick, New York (848 MW)
3.	Pilgrim 1, Massachusetts (677 MW)
4.	Ginna, New York (581 MW)
5.	Three Mile Island 1, Pennsylvania (805 MW)[41]
6.	Byron 1 & 2, Illinois (2,346 MW)[42]
7.	Quad Cities 1 & 2, Illinois (1,819 MW)[43]
8.	Davis Besse, Ohio (894 MW)
9.	Oyster Creek, New Jersey (615 MW)[44]

To put that in perspective, that same 75 terawatt-hours of low-carbon electricity per year from nuclear would be equal to more than three times as much electricity as was produced from all U.S. solar and nearly half as much as was produced from all U.S. wind projects in 2014.[51]

Illustrating the importance of nuclear energy's role in the production of low-carbon electricity can also be done by comparing it with the output of renewable energy in other countries. Doing so shows that replacing 10 gigawatts of U.S. nuclear capacity with solar energy would require installing about twice as much solar capacity as now exists in Germany. Replacing that same U.S. nuclear capacity solely with wind would require installing about 1.5 times as much wind-energy capacity as now exists in Spain.

Germany has long been a world leader in solar-energy production. In 2014, Germany produced nearly one-fifth of the world's solar electricity;[52] its solar sector produced twice as much energy from the sun as America's; and Germany now produces about 35 terawatt-hours of electricity from about 38 gigawatts of installed solar capacity. To match the low-carbon electricity output provided by 10 gigawatts of U.S. nuclear capacity, America would have to install roughly 80 gigawatts of new solar capacity, or about twice Germany's total existing solar capacity.

Germany's ongoing push to add more solar capacity has been costly. Over the past half-decade or so, electricity prices for industrial users in Germany have increased by about 60 percent, and the country's big industrial companies have repeatedly complained about the rising cost of energy and their ability to compete with foreign companies.[53] In mid-2014, according to a *Financial Times* article, industrial electricity rates for midsize German companies were nearly twice the prevailing rates for similar industrial companies located in Texas.[54]

Residential electricity rates in Germany have also increased. Between early 2007 and late 2014, residential electricity prices (including all taxes) rose by more than 40 percent, jumping from $0.23 to $0.33 per kilowatt-hour, according to data from Eurostat.[55] Those rates increased at the same time that Germany's solar capacity increased 17-fold and wind capacity more than doubled.[56]

Like Germany, Spain has avidly pursued renewable energy and, like Germany, has seen significant increases in its electricity prices. Since 2005, Spain has more than doubled its production of electricity from wind. In 2014, Spain was the second-largest wind producer in Europe (and fourth-largest internationally), with production of about 52 terawatt-hours of electricity, from 23 gigawatts of installed wind capacity.[57] Thus, to produce the 75 terawatt-hours of low-carbon electricity generated by 10 gigawatts of U.S. nuclear would require installing about 1.5 times the amount of wind capacity now operating in Spain—or roughly 34 gigawatts of new wind capacity. Stated differently, this would require about a 50 percent increase in the capacity of the existing fleet of U.S. wind turbines.

While wind energy's costs have declined in recent years, Spanish consumers have seen their bills increase along with the expansion of solar and wind energy in that country. Between 2007 and 2014, when wind capacity increased by about 50 percent and solar capacity grew about sevenfold, residential electric rates in Spain surged by 69 percent.[58] Spanish households now pay some of the highest electricity prices in Europe—about $0.27 per kilowatt-hour, more than twice the U.S. average.[59]

Given wind energy's dominant role in the U.S. renewable-energy sector (in 2014, wind energy produced about 184 terawatt-hours of electricity, roughly ten times more than solar), it is worthwhile to consider the implications of supplanting all U.S. nuclear-energy production with wind. In 2008, the DOE estimated that about 300 gigawatts of wind capacity would be required to provide 20 percent of U.S. electricity by 2030.[60] For perspective, the U.S. had about 66 gigawatts of wind capacity in 2014.[61]

The DOE's estimate of 300 gigawatts of capacity may understate the actual amount of generation capacity (and resultant land use) that would be required: the latest estimate of the U.S. Energy Information Administration (EIA) shows that U.S. electricity demand will likely total 4,400 terawatt hours in 2030.[62] If wind energy is to meet the 20 percent goal, it will have to produce about 880 terawatt-hours of electricity by 2030.

During the past ten years, the productivity of the U.S. wind-energy sector has averaged 2.4 terawatt-hours per gigawatt of installed capacity. Globally, the average is lower, about 1.8 terawatt-hours per gigawatt of capacity. Even if we use the higher productivity figure from U.S. wind (2.4 terawatt-hours per gigawatt), producing 880 terawatt-hours of electricity from wind would require about 367 gigawatts of wind capacity, or nearly six times as much capacity as the U.S. had in 2014.

To put 367 gigawatts of wind capacity in perspective, consider that between 2005 and 2014, the U.S. wind sector grew by an average of about 6.5 gigawatts annually.[63] If America's wind sector continues growing at its historical average, it would take about 46 years for it to reach the 367 gigawatts of capacity needed to provide 20 percent of U.S. electricity.

There are also important qualitative differences between the electricity provided by nuclear plants and that provided by renewables. The pending retirement of a significant swath of U.S. reactors is occurring at the same time that America is retiring dozens of gigawatts of coal-fired power plants. The result of these ongoing retirements is that the U.S.

will have fewer electricity generation units that can provide baseload electricity—the power that forms the backbone of the modern electric grid. Without those baseload plants, and in the absence of large-scale (and ultracheap) methods of storing electricity, it is likely that America's grid will become less reliable and more expensive to maintain.

IV. FACTORS DRIVING THE DECLINE

A recent Gallup poll found that 51 percent of Americans favor the use of nuclear energy.[64] Further, there appears to be significant support for addressing climate change, as some 55 percent of Americans believe that humans are causing changes in the Earth's temperature.[65] But public support for nuclear energy cannot by itself overcome the challenges facing the technology. Indeed, the list of challenges is long and includes the following:

High costs and project delays

Electricity producers in the U.S. and Europe that decide to build new nuclear reactors are, in effect, making bet-the-company wagers. The Plant Vogtle expansion in Georgia, which includes two new reactors with output of about 2,200 megawatts, is projected to cost $14.5 billion and was originally expected to begin producing electricity in 2016.[66] Because of delays, the project is now expected to begin operating in mid-2019. Such delays are costly. In January 2015, Oglethorpe Power Corporation, which owns a 30 percent stake in the Plant Vogtle reactors, revealed that each month that the project is delayed increases costs by about $28 million.[67]

Delays only add to the high price of nuclear when compared with other generation options. Based on the cost of the reactors being built at Plant Vogtle, the current installed cost of new nuclear capacity is about $6.6 million per megawatt. For comparison, the Prairie State Energy Campus, a 1,600 megawatt coal-fired power plant in southern Illinois, which began generating electricity in 2012, cost about $4.4 billion to build. To be clear, there are no new coal-fired power plants now under construction in the United States. And given the prospect of the EPA's Clean Power Plan, it is highly unlikely that any new coal plants will be built in the near future. But if a generator decides to use coal-fired technology, that new capacity will likely cost about the same as Prairie State: about $2.75 million per megawatt.[68]

Natural gas–fired plants are even cheaper than nuclear or coal. Portland General Electric is building a 440-megawatt gas-fired plant in Oregon for $450 million, or about $1 million per megawatt.[69] Although the ongoing fuel costs for gas-fired units are higher than those for nuclear plants, the higher capital costs of nuclear are prohibitive for most companies seeking to add capacity.

High costs and project delays are also hampering the deployment of nuclear energy in Europe. Consider the ongoing problems in the construction of a new reactor design, known as the European Pressurized Reactor (EPR), being built by French nuclear company Areva, in western Finland. Construction on the 1,600-megawatt reactor, located on Olkiluoto Island, began in 2005 and was supposed to be completed by 2009.[70] The latest delays have pushed the start-up date for the reactor to 2018. The final cost of the project is likely to be more than 9 billion euros, roughly three times the original cost estimate.

Areva is also facing problems with an EPR that it is building in Flamanville, France. In April 2015, the company announced that there may be imperfections in the steel used to make the caps on the main reactor vessel. If those imperfections are deemed serious, the entire vessel may have to be removed and replaced, a move that could add hundreds of millions of dollars to the project's cost.[71] Construction on the Flamanville reactor began in 2007 and was expected to be complete by 2013.[72] Now it is not clear when Flamanville will begin operating.

Low-cost natural gas

In 2011, shortly after Japan's Fukushima disaster, a senior executive at a large U.S. electric utility lamented nuclear energy's high cost when compared with lower-cost options, such as natural gas–fired generation. "How can you compete with natural gas when it's priced at less than $4?" asked the executive. The answer, he said, is, "you can't."

Since 2011, the price of natural gas has descended even lower. These prices are being closely watched by Exelon and other nuclear utilities. In January 2015, Michael Pacilio, a top Exelon executive, said that in order to justify the construction of a new nuclear plant in the U.S., natural gas prices would have to be at least $8 per million BTU. Pacilio added that regulators would have to impose an additional $8 in carbon taxes or cap-and-trade policies for nuclear to be justified. (The current spot price for natural gas is less than $3.)[73]

It is not clear how long today's natural gas prices will prevail. The shale revolution has unlocked vast quantities of new natural gas supplies in the U.S., which has resulted in record gas production. America now has so much gas that it will soon be a significant player in the global LNG export market. This abundance of natural gas and the ability of U.S. drillers to ramp up supply by drilling more wells ensures that natural gas prices will likely stay significantly below the $8 threshold for years to come. That means that any new nuclear projects—regardless of the reactor design—will face a difficult economic hurdle.

Lack of electricity-demand growth

Nearly all the existing U.S. nuclear plants were built during a period of robust growth in electricity demand. They were built in the 1970s and 1980s, when the country was amid scares about peak oil, natural gas shortages, and oil price spikes. None of those factors is in play today. Thanks largely to government-mandated energy-efficiency measures, U.S. electricity demand has plateaued. For instance, in 2013, U.S. electric generation was about 4,200 terawatt-hours[74]—about the same as in 2005. Given lackluster demand growth, it seldom makes economic sense for utilities to add large generation units (those with capacity of 1,000 megawatts or more) to their portfolios. Unfortunately for the nuclear industry, nearly all the reactors now being built for commercial applications have capacities of 1,000 megawatts or more.

By contrast, generators can purchase additional gas-fired power units in a staggering array of sizes, from as small as a few kilowatts to several hundred megawatts. General Electric is selling a natural gas–fueled reciprocating engine, the Jenbacher J920, that is 49 percent thermally efficient and generates 9.5 megawatts.[75] Smaller-generation units require less capital and, therefore, have less long-term price risk for electricity providers.

Subsidized renewable energy is driving down the wholesale price of electricity

Nuclear reactors are designed to run at full output, 24 hours per day. The owners of reactors make money based on the average price of electricity in the wholesale market, over the course of a full day. But over the past few years, increased use of renewable energy in general—and wind energy, in particular—has resulted in significant decreases in the price of wholesale electricity. This has occurred largely because wind energy gets a hefty subsidy, in the form of the production tax credit, which pays the owners of wind projects 2.3 cents for each kilowatt-hour of electricity that they produce.[76] The result of these subsidies: owners of wind projects can bid negative prices (i.e., they can pay the grid operator to take their electricity) so that they can continue collecting the federal subsidy.

Before 2006, when the wind industry began growing rapidly, negative prices in the wholesale electricity market were rare. In the past few years, negative pricing has become common in several markets across the country. Negative prices are hurting owners of conventional power plants in general and nuclear plants in particular. In 2013, Exelon, which owns the Clinton and Quad Cities nuclear plants in Illinois, said that it was seeing negative prices in the markets served by those reactors as much as 14 percent of the time during off-peak hours.[77] Exelon points to the proliferation of wind-energy projects in Illinois as a key reason for those negative prices. The Quad Cities plant, which has about 1,800 megawatts of capacity, is one of the reactors that may be shut down in the next few years.

A 2012 study of the production tax credit, by David Dismukes of the Center for Energy Studies at Louisiana State University, concluded that the subsidy for wind-energy production harms "reliability by penalizing the conventional generators needed to backstop wind when it does not blow, forcing conventional generators to operate at a loss or not at all." Dismukes's study, commissioned by the American Energy Alliance, a not-for-profit group that supports free-market energy policies, calculated that wind-energy producers can tolerate negative wholesale prices of as much as $34 per megawatt-hour and still make a profit. The production tax credit, he found, "distorts markets and allows wind to compete unfairly with both conventional generation resources and even other types of renewables."[78]

In 2013, U.S. subsidies for solar and wind energy totaled $10.3 billion, according to the EIA—about six times more than was provided to nuclear, which received about $1.7 billion. The same EIA report shows that in 2010, U.S. solar- and wind-energy subsidies totaled $6.5 billion, more than three times the amount provided to nuclear, which received subsidies totaling $1.9 billion.[79]

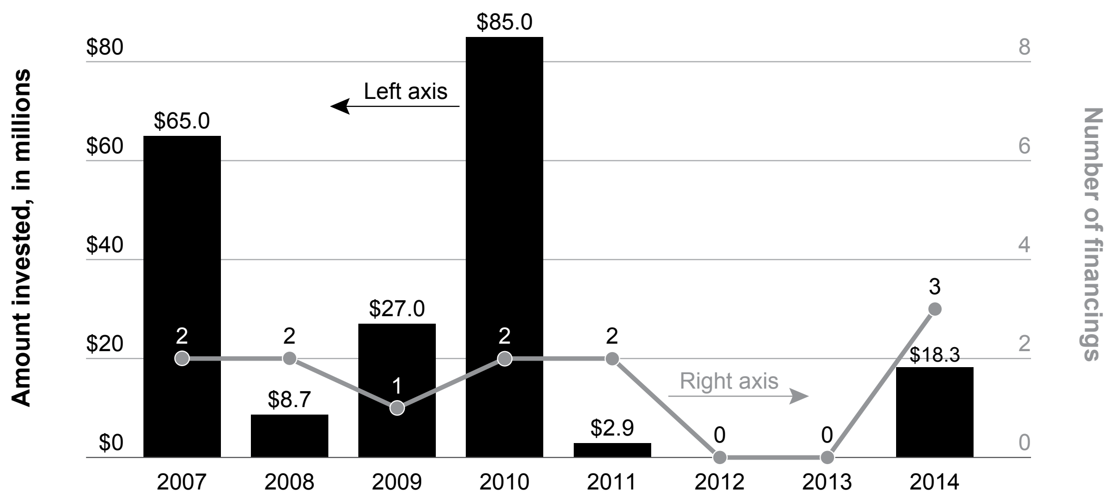
In May 2015, Alex Trembath, an energy analyst at the Breakthrough Institute, an environmental policy group, used the EIA's report to calculate the subsidies based on the amount of energy produced by each form of generation. Trembath found that in 2013, solar energy received $280 in subsidies per megawatt-hour of electricity produced; wind energy received about $35 per megawatt-hour. By contrast, subsidies for nuclear totaled about $2 per megawatt-hour, and subsidies for coal-fired electricity totaled about $0.69 per megawatt-hour.[80] Little surprise that the electric utilities are complaining about a nonlevel playing field that favors renewables over conventional forms of generation.

Private-sector financial support for nuclear start-ups has been modest

An important indicator of a technology's promise is the amount of venture capital that it can raise. In 2014, start-ups in America's nuclear-energy sector raised less than $20 million, while no such investments were made in 2012 and 2013 (**Figure 6**). And the 2014 sum was just a quarter of the amount raised in 2010. One of the highest-profile start-ups in the nuclear sector, Transatomic, raised $2.5 million in 2014.[81]

However, these figures may understate the amount of capital being invested in new nuclear technologies.

Figure 6. Venture Investment in U.S. Nuclear-Energy Start-Ups, 2007–14



Source: Dow Jones VentureSource, VentureWire

A June 2015 report by Third Way, a bipartisan think tank based in Washington, D.C., estimated that some 50 companies "backed by more than $1.3 billion in private capital" are now developing new reactor designs.[82] While $1.3 billion is a significant sum, some perspective is needed.

The electricity business is enormous. U.S. electricity sales now total nearly $400 billion annually.[83] The global electricity sector has revenues of about $2 trillion annually.[84] Even if all of the $1.3 billion that is reportedly backing advanced nuclear-energy companies is spent, it will remain a tiny fraction of the overall potential market.

Research and development budgets of major corporations reveal that the amount being spent on advanced nuclear is not very significant. In 2014 alone, auto giant Volkswagen spent $13.5 billion on R&D. Google spent $8 billion, and Ford spent $6.3 billion.[85] Again, these numbers are for a single year. If advanced nuclear technology is going to make significant inroads against traditional forms of generation, it will have to garner far more R&D funds than it does now.

Lack of political support in Washington

It is true that the Obama administration has been generally supportive of the nuclear sector; it is also true that the nuclear industry simply does not have as broad a base of support on Capitol Hill as do some of its competitors in the energy sector. That weakness is due, in part, to nuclear's relative newness when compared with the long-established lobby and support networks that have been developed over many decades by the oil, natural gas, and coal industries. Unlike those industries, which have created a number of wealthy individuals who are ready and willing to make significant donations to politicians and political parties to promote their interests, America's nuclear industry lacks a single identifiable tycoon.

In addition, America's hydrocarbon sector is concentrated geographically. Oil and gas production is a major player in states such as Texas, Oklahoma, North Dakota, and Louisiana. Coal is a big economic factor in Kentucky, West Virginia, and Wyoming. By contrast, the nuclear industry has a smaller, less prominent, geographical footprint. That smaller footprint has meant fewer members of Congress who are willing to vocally advocate for nuclear energy.

The lack of political support for nuclear energy also stems from ideological differences between Republicans and Democrats. As one DOE official explained it, nuclear-energy needs robust government support and cannot garner bipartisan support because Republicans are generally "pronuclear and antigovernment. And Democrats are pro-government but antinuclear." In short, advocates for nuclear energy on Capitol Hill tend to be Republicans and have very few Democratic allies.

In its last two presidential platforms, the Republican Party has stated its support for nuclear energy.[86] In 2008, for example, the GOP called nuclear "the most reliable zero-carbon-emissions source of energy that we have."[87] By contrast, the last two Democratic presidential platforms barely even nodded at nuclear energy.[88] Its 2012 platform, for instance, uses the term "nuclear energy" just once, and that mention occurs only in reference to nuclear proliferation.[89]

Such platforms reflect the beliefs of their constituents. A March 2015 Gallup poll showed that, among the general public, voters who identify as Republican are about twice as likely (47 percent to 24 percent) to support nuclear energy as are those who identify as Democrats.[90] Senator Harry Reid, the powerful Democrat (and former majority leader) from Nevada, has effectively blocked the Yucca Mountain nuclear-waste repository for years. In May 2015, after a pair of Republican presidential candidates, Marco Rubio and Jeb Bush, were questioned about their positions on the Yucca Mountain waste repository, Reid issued a statement that said: "Let me be as clear as can be, Yucca Mountain is dead. It is not coming back. And I dare any Republican to step foot in Nevada and declare their support for it."[91]

While the Democratic Party and Reid oppose nuclear, the Obama administration has been supportive. The DOE has provided some $8.3 billion in loan guarantees to owners of the Plant Vogtle reactors.[92] The agency is also providing grants for the development of small modular reactors (SMRs). But the president has scarcely mentioned nuclear energy since 2009, when, during a speech, he staunchly advocated for the use of nuclear to fight climate change.[93] As long as the Democratic Party remains opposed to nuclear energy, an end to the stalemate on the nuclear-waste issue—and, more broadly, a renaissance of American nuclear power—will be difficult to achieve.

Nuclear waste

Antinuclear activists have long claimed that nuclear energy cannot be a viable option because the U.S. lacks a place to safely store the radioactive waste generated by commercial nuclear reactors. In fact, since 1976, the state of California has prohibited the construction of any new reactors until the federal government establishes a permanent repository for high-level nuclear waste.[94] Seven other states have similar bans.[95]

More than 30 years ago, Congress passed the Nuclear Waste Policy Act, which mandated that the DOE begin taking spent nuclear fuel by 1998. Yet today, the federal government is no closer to solving the spent-fuel issue than when that legislation was passed in 1982. The nuclear-waste repository at Nevada's Yucca Mountain has been studied for decades and has cost consumers billions of dollars; but the Obama administration has announced that it is abandoning Yucca Mountain as a repository and is seeking another location.

Lacking any other centralized repository, spent fuel is now being stored on-site at nuclear plants, first in specially built spent-fuel pools and then in large steel and concrete "dry-cask" containers. At the end of 2014, about 76,000 metric tons of spent nuclear fuel were being stored at locations in about three dozen states across the country.[96]

According to the Nuclear Energy Institute, an industry trade group, the federal government has collected about $36 billion from nuclear utilities to help fund the siting and construction of a long-term nuclear-waste repository. But the federal government still has not fulfilled its responsibilities under the Nuclear Waste Policy Act. Because the government is not fulfilling its legal obligations, utility companies have been taking legal action against the government for not taking the waste. And they have been winning. More than 70 legal settlements have been made thus far, at a cost to the government of about $4 billion. Energy Secretary Ernest Moniz has estimated that if the government does not resolve the waste issue soon, the government's legal liabilities over the next half-century could be as much as $23 billion.[97]

After decades of wrangling, the simple truth is that the U.S. has the technical ability to develop a nuclear-waste disposal site but lacks the political will to make such a site a reality. Unless or until the federal government gets serious about fulfilling its legal responsibility for accepting waste from the companies that generate nuclear power, the industry will continue to be hamstrung.

Increased regulation

Managers in the nuclear sector have a term for the increased costs incurred when federal authorities impose new regulations: the "safety-cost ratchet." The industry was hit with a wave of new regulations after the September 11, 2001, terrorist attacks. It was hit with another wave of regulations after the accidents at Fukushima. If something goes wrong at a commercial reactor, says one nuclear-industry veteran, "we bolt something else onto it: new equipment, a new inspection requirement, a new procedure."

After the Fukushima accident, the NRC required owners of reactors to beef up their emergency preparedness, assess their facilities for possible seismic and flood events, and ensure safety of operations in case of a loss of electricity to the plant.[98] While each of these requirements may make sense, each new rule added to the existing regulatory scheme causes operating costs to increase. For instance, in mid-2015, the Tennessee Valley Authority completed a series of NRC-

WATTS BAR UNIT 2: 42 YEARS FROM START TO FINISH

The malaise in America's nuclear sector is exemplified by the reactor known as Watts Bar Unit 2 (**Figure 7**), located near Spring City, Tennessee. In 1973, the Tennessee Valley Authority (TVA) began construction on the reactor.[100] Fifteen years later, with the project partially completed, work was halted. In 2007, work on the reactor was resumed, with a projected cost of $4.2 billion to complete the 1,150-megawatt project.[101] If all goes as planned, Watts Bar Unit 2 should begin producing electricity at the end of 2015.[102]

From the time construction began to the time Watt Bar Unit 2 will finally begin producing electricity, 42 years will have passed. In 1973, when the TVA began construction on the reactor, the U.S. was producing more than half of all the nuclear energy produced globally.[103] Over the next three decades, America's nuclear sector expanded rapidly, with output increasing nearly tenfold. Since 2000, however, the industry has been stuck in neutral. In 2013, America's nuclear sector produced about the same amount of electricity (about 800 terawatt-hours) as it did in 2000.[104]

The problems with the Watts Bar reactor—in particular, the high cost and long delay in bringing it online—involve the same issues that have plagued the U.S. nuclear sector for decades. In addition to the Watts Bar reactor, four other reactors—all Westinghouse AP1000s—are currently under construction. Two reactors are being built at Plant Vogtle and another two at the V. C. Summer plant in South Carolina.[105] The total capacity of these four reactors will be about 4.4 gigawatts. Thus, the amount of new nuclear capacity now being added in the U.S. totals about 5.5 gigawatts.

Figure 7. Watts Bar Nuclear-Generating Station

Source: Tennessee Valley Authority[106]

ordered safety upgrades at three nuclear facilities: Sequoyah, Browns Ferry, and Watts Bar. The cost of those upgrades, which were ordered after Fukushima, cost the TVA $180 million.[99]

V. THE CASE FOR NUCLEAR

Shortly before World War I, Winston Churchill, then First Lord of the Admiralty, said that when it comes to energy security, "Safety and certainty in oil lie in variety and variety alone." Churchill's statement also applies to electricity generation. An electric grid that is diversified and that does not rely too much on a single form of generation helps ensure security of supply. The reliable generation provided by nuclear reactors is a critical part of that diversity of supply.

The importance of diverse generation assets was seen in early 2014 during a particularly cold period, known as a polar vortex, that hit much of the continental United States. During the freezing weather, electricity demand skyrocketed, as did demand for natural gas, which was being used for heating as well as electricity production. But there was not enough natural gas transportation capacity to meet the surge in demand. This was especially true in New York and New England, areas that lag the rest of the country in gas-pipeline infrastructure. Some coal- and oil-fired generators were unable to operate because of the extreme cold.

At the height of the cold front, PJM Interconnection, the largest U.S. grid operator, saw record demand of about 141,500 megawatts, but about 20 percent of the generators in PJM's territory were unable to operate because of the cold. Fortunately, America's fleet of nuclear reactors was able to operate at about 95 percent of design capacity during the polar vortex. That reliable nuclear generation was critical, as grid operators worked to avoid brownouts and blackouts.[107]

As discussed, many factors are likely to decrease nuclear energy's share of the electricity-generation mix in the coming years. At the same time, federal regulations, including the Clean Power Plan, will be decreasing the amount of coal-fired electricity generation.

Between 1990 and 2012, natural gas's share of U.S. electricity production jumped from 12 percent to about 30 percent. The EIA expects that by 2040, that share could increase to 35 percent. The EIA is also projecting that nuclear's share of the market will decline from the current 20 percent to about 16 percent and that coal's share will fall from about 39 percent today to 32 percent by 2040. While the shale revolution has resulted in record production of natural gas, it is possible that the U.S. will become too reliant on natural gas–fired electricity. That reliance could result in brownouts and blackouts.

In late 2014, the North American Electric Reliability Corporation, the regulatory authority that aims to ensure the reliability of the grid in North America, said that while natural gas–fired power plants can provide more baseload capacity to replace retired nuclear and coal plants, "higher dependence on natural gas can expose additional reliability risks." It added that, as gas is used to produce more electricity, "unforeseen events like the 2014 polar vortex could disrupt natural gas supply and delivery for the power sector in high-congestion regions, increasing the risk for potential blackouts."[108]

In addition to diversity of supply in U.S. generation, the case for nuclear includes recognition of America's decades-long role as a pioneer in nuclear-energy deployment and thus in the development of technologies for carbon-free electricity generation. For decades, the NRC has been seen as the global gold standard for design certification and safety protocols. While the agency has plenty of critics, it has also had a remarkably good record on safe operations.

As new companies seek to bring new reactor technologies to market, it makes sense, economically and environmentally, for the NRC to maintain its leadership role. If start-up companies are not able to get governmental cooperation from the U.S. as they seek to bring their reactors to market, they will take their employees, and their capital, elsewhere. U.S. policymakers must understand that America could cede its role in nuclear technology to other countries, such as China, Canada, or Russia.

The case for nuclear should include the recognition that advanced nuclear technology must be brought to bear if we are to have any hope of slowing the rate of growth in global carbon-dioxide emissions. If the NRC and the DOE do not actively support the development and licensing of new reactor designs—specifically, reactors that could be safer and cheaper to operate than existing designs—electricity generators in America and abroad will have no choice but to continue relying on coal and natural gas to provide baseload power for customers. That, in turn, will ensure that global carbon-dioxide emissions will continue to rise.

Finally, the case for nuclear requires examining how best to encourage the continued operation of existing reactors. As noted, many reactors are facing economic headwinds. Unless owners of those plants are able to keep them operating profitably, the U.S. could see the closure of about 10 gigawatts of nuclear capacity. Given the cost of new reactors, it will be far cheaper to keep those plants operating than it will be to build new nuclear capacity. Nuclear-sector analyst Ed Kee, who heads the Nuclear Economics Consulting Group, has suggested several options to help owners of struggling plants keep their reactors online. One such option: allow owners to enter into a contract for difference (CfD).

CfDs would be funded by the government and would ensure that owners of reactors receive prices for their electricity that support continued operation. For instance, if wholesale electricity prices dip below the break-even price for electricity produced by a reactor for a specified period, the CfD could be invoked to allow the reactor's owner to be made whole, based on the difference in the clearing price and the owner's costs.[109] This would be a subsidy; but if the federal government is going to provide subsidies for renewable-energy sources, such as solar and wind, it should consider how to encourage existing nuclear plants—the biggest and, arguably, the most important producers of low-carbon electricity—to keep operating.

VI. ENCOURAGING A NEW GENERATION OF NUCLEAR

While the myriad challenges facing nuclear energy are daunting, the U.S. can still maintain its dominant position on nuclear technology. Doing so will require more government support. Specifically, it will require government-funded real estate and research, as well as a faster testing and licensing process for new reactor technologies.

Perhaps the most pressing need facing the companies that are pursuing new reactor designs is access to a new test reactor. Such a reactor will enable them to benchmark their fuel mixes and designs. Several countries have test reactors, including Japan, China, and Russia. France is building a test reactor, with construction expected to finish in 2015 or 2016.[110] (The U.S. has a test reactor at Idaho National Laboratory,[111] but it cannot handle the heat and radiation levels that will be produced by the advanced reactors now being developed.)[112]

America has plenty of real estate that could provide a home for a new test reactor. From Idaho to Los Alamos, Oak Ridge to Brookhaven, the U.S. has a spate of national laboratories that would be compatible homes for a test reactor. Some investors in nuclear start-up companies are advocating a public-private partnership in a campus that would include a test reactor. Such a campus would then become a research center for the companies trying to commercialize new reactor designs.

Government support for a test reactor is essential if the U.S. is to be in the vanguard of a new class of promising reactors, SMRs. The global reactor fleet is dominated by designs that typically have power outputs of 1,000 megawatts or more. By contrast, SMRs have outputs ranging from 1–2 megawatts to 500 megawatts.

SMRs are not a new idea. The U.S. Navy has been using scaled-down nuclear reactors for decades and now operates a fleet of 86 nuclear-powered submarines and ships.[113] Yet in addition to their reduced size, the new breed of SMRs being designed for commercial-electricity production generally have fewer components than their predecessors and tend to rely on simpler safety systems. Some use gravity to circulate cooling water in case electrical power is lost at the site of the reactor. They may also use convection and conduction to remove excess heat from the reactor core. Such features can allow the SMR to remain safe, even in the case of a power outage, for a week or longer. Other features of SMRs that should make them cheaper to build and safer to operate include plans to install the reactor in underground containment systems, which will reduce the plant's surface footprint and help protect it from aircraft impact and other terrorist threats.

In 2013, during testimony before the Senate Energy and Natural Resources Committee, Energy Secretary Moniz said: "We believe SMRs will be part of the future model of nuclear energy worldwide."[114] But if SMRs are to achieve commercial viability, the NRC will need a faster, cheaper licensing process. By any reasonable measure, the NRC's licensing process is cumbersome and long. One lobbyist who represents nuclear-energy clients in Washington, D.C., estimates that getting a license from the NRC for a new reactor design requires spending about $500 million and takes five years or longer.

NuScale Power LLC, an Oregon-based company owned by construction giant Fluor Corporation, is planning to submit a design-certification application to the NRC for its SMR. NuScale's application will contain about 12,000 pages.[115] That is an extraordinary volume of data, particularly given that NuScale is planning to build a light water reactor—the same technology commonly used today. Indeed, NuScale's design is simply a smaller version of the large reactors used worldwide. (All the commercial reactors now operating and all the reactors now being built in the U.S. are light water reactors.)[116] The electrical output of each NuScale reactor is projected to be 50 megawatts.[117] By contrast, the Westinghouse AP1000, the reactor type being built at Plant Vogtle, has an electrical output of 1,110 megawatts.[118]

In addition to its familiar design, NuScale has other advantages over its competitors. It is slated to receive $217 million in grants from the DOE.[119] The company has announced plans to build its reactor on federal land, at Idaho National Laboratory. The electricity that it produces will be purchased by Utah Associated Municipal Power Systems.[120] Although it has a financially secure parent company, federal grant money, a federally owned site for its project, and a customer for its electricity, NuScale executives are predicting that the soonest they may be able to produce electricity from their reactor is 2023.

Given the regulatory hurdles and long lead times facing NuScale, it is easy to understand why other nuclear start-ups that are relying on different cooling technologies—such as liquid metal or gas—will face an even more difficult licensing process at the NRC.

Regulatory challenges at the NRC are so daunting that one prominent start-up, Terrestrial Energy, which plans to build a reactor that uses molten salt, has moved its offices to Ontario, where it plans to pursue licensing through the Canadian Nuclear Safety Commission. Molten-salt reactors use nuclear fuel dissolved in a molten fluoride or chloride salt. The molten-salt solution functions as the fuel, which produces the heat, as well as the coolant, which transports the heat to the rotating turbogenerators that produce the electricity. The design was proved at Oak Ridge National Laboratory, where a molten-salt reactor operated during 1965–69.[121]

The federal government must play a role in licensing new nuclear reactors and monitoring reactors for safety; it must also face its responsibility for nuclear-waste disposal. Handling and disposal of nuclear waste has never been a technical problem: the federal government has plenty of real estate on which it can store all the nuclear waste generated by America's nuclear reactors. Rather, it has always been a political problem.

The problem will require resolve on the part of Congress and the White House. The resolve to take action could include going forward with the waste repository at Yucca Mountain (which the NRC recently said passes all technical specifications) or allowing the waste to go to other federal locations, including the Waste Isolation Pilot Plant in New Mexico and some of the national laboratories. Alternatively, Congress could pay the nuclear utilities to store their radioactive waste in dry casks at the sites of the various reactors, a storage method that has been proved safe and effective.

CONCLUSION

While scientists and activists can debate the societal risks of climate change, it is readily apparent that any realistic strategy that seeks to reduce the growth of carbon-dioxide emissions must include nuclear energy. Even without the risks of climate change, there is a strong incentive to increase cleaner production of electricity so as to reduce production of traditional air pollutants, such as NOx, SOx, heavy metals, and particulates, which pose threats to public health.

Unquestionably, nuclear energy faces many hurdles, including high construction costs and competition from low-cost natural gas. Clearly, the U.S. should maintain a diverse portfolio of generation assets in the electric sector. And America needs a more productive approach to encouraging the development of advanced nuclear technologies, particularly SMRs.

In an April 2009 speech in Prague, President Obama said: "We must harness the power of nuclear energy on behalf of our efforts to combat climate change."[122] If the U.S. is to continue leading the world in nuclear energy—and therefore in reducing the rate of growth in carbon-dioxide emissions—the federal government must take an active role by providing the physical infrastructure, research capabilities, and regulatory support that such technologies will require as they are readied for commercial deployment. Specifically, the federal government should:

1. **Resolve the nuclear-waste issue.** The haggling over Yucca Mountain has lasted far too long. It is time for the federal government to accept its legal responsibility to accept radioactive waste from nuclear utilities.
2. **Level the playing field in electricity production.** Allow nuclear to compete more favorably with heavily subsidized renewable sources, such as wind and solar.
3. **Streamline and accelerate the NRC's permitting process for SMRs.** Doing so will help ensure America's continued leadership in nuclear-energy development and licensing.
4. **Ensure continued operation of existing reactors.** The DOE should investigate how to bolster economic support to nuclear reactors.
5. **Nurture America's nuclear sector.** Congress must take a more active role by providing a campus for advanced nuclear research, as well as funding for a test reactor.

Appendix A

Types of Nuclear Reactors (descriptions provided by the Nuclear Energy Institute)[123]	
Light Water Reactors	These designs are the most compatible with the existing federal-regulatory framework. This technology is used in all the existing U.S. nuclear power reactors, as well as the five large reactors now being built in Tennessee, Georgia, and South Carolina. Among other applications, small light water reactors could replace older fossil-fired power stations of similar size that may no longer be economical to operate in a carbon-constrained world. The infrastructure, cooling water, rail, and transmission facilities already exist at such facilities.
High-Temperature Gas-Cooled Reactors	HTGRs are well suited to provide process heat for the industrial and transport sectors in the medium term and hydrogen in the longer term, while reducing the carbon footprint of these activities.
Liquid-Metal and Gas-Cooled Fast Reactors	These reactors are suitable for distributed nuclear applications for electricity, water purification, and district heating in remote communities. They could use recycled nuclear fuel and support nonproliferation efforts by consuming material from nuclear weapons, thus eliminating it as a threat.

Appendix B

Companies Developing Small Modular Reactors

Company	Technology	Reactor Capacity	Headquarters	Website
Flibe Energy	Molten salt—thorium	10–250 MW	Huntsville, AL	flibe-energy.com
Gen4 Energy	Lead-cooled fast reactor	25 MW	Denver, CO	www.gen4energy.com
TerraPower	Sodium fast reactor	550+ MW	Bellevue, WA	terrapower.com
Transatomic	Molten salt	550 MW	Cambridge, MA	transatomicpower.com
Terrestrial Energy	Molten salt—thorium	30–300 MW	Mississauga, ON	terrestrialenergy.com
Thorcon	Molten salt—thorium	250 MW	Tavernier, FL	thorconpower.com
Thorium Power Canada	Thorium solid fuel	10 MW	Toronto, ON	www.thoriumpowercanada.com
UPower	Micro reactor	1.0–1.5 MW	Boston, MA	www.upowertech.com
NuScale Power	Light water reactor	45 MW	Corvallis, OR	www.nuscalepower.com
General Atomics	Gas fast reactor	265 MW	San Diego, CA	www.ga.com/energy-multiplier-module

Endnotes

1. See http://www.world-nuclear.org/info/facts-and-figures/nuclear-generation-by-country.
2. See http://www.world-nuclear.org/Nuclear-Basics.
3. See http://www.climatecentral.org/blogs/helpful-energy-comparisons-anyone. See also http://www.answers.com/Q/How_many_homes_can_a_gigawatt_power.
4. *Oil: Discover the Story of Petroleum, and the Many Ways It Shapes the World We Live In* (New York: DK, 2007), 67–68, http://books.google.com/books?id=dknlH_8XRRwC&pg=PA65&lpg=PA65&dq=poland+oil+lamps+and+carpathian+mountains&source=bl&ots=mp9E7dV6Vo&sig=dYPmf5SIi3alFTYiBBsjFsLSnWQ&hl=en&sa=X&ei=NR_oUa35Aoj7rAHEgYHIDA&ved=0CFQQ6AEwBQ#v=onepage&q=poland%20oil%20lamps%20and%20carpathian%20mountains&f=false.
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12. Solar Energy Industries Association (SEIA), http://www.seia.org/policy/solar-technology/photovoltaic-solar-electric.
13. Paul Brown, "First Nuclear Power Plant to Close," *The Guardian*, March 21, 2003, http://www.guardian.co.uk/uk/2003/mar/21/nuclear.world.
14. See http://en.wikipedia.org/wiki/Shippingport_Reactor.
15. See http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors.
16. See http://www.eia.gov/tools/faqs/faq.cfm?id=228&t=2.
17. See http://www.powermag.com/americas-aging-generation-fleet.
18. See http://www.scientificamerican.com/article/nuclear-power-plant-aging-reactor-replacement-.
19. See http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Environment-Emissions-Prevented.
20. In 2014, U.S. CO2 emissions totaled 6 billion tons. See *BP Statistical Review of World Energy 2015* (hereafter, *BP 2015*).
21. The American Wind Energy Association claims that in 2013, wind energy avoided about 96 million tons of carbon dioxide. See http://www.awea.org/Resources/Content.aspx?ItemNumber=5097. During 2013–14, U.S. wind-energy production grew by 8 percent, from 169 TWh to 183 TWh. This paper assumes that, in 2014, wind energy achieved carbon-emissions reductions of about 104 million tons.
22. The SEIA claimed that existing solar capacity "offset 16.8 million metric tons of CO2" in 2013. See http://www.seia.org/research-resources/cutting-carbon-emissions-under-111d-case-expanding-solar-energy-america. Given that U.S. solar capacity increased by about 50 percent during 2013–14, this paper assumes that solar now avoids about 26 million tons of carbon-dioxide emissions. This number seems high, given that solar-energy production in 2014 was 18.5 TWh, about one-tenth the production derived from wind energy that year (183.5 TWh). Thus, despite generating one-tenth as much electricity as wind, the solar association is claiming that it achieves carbon-emissions reductions equal to about one-fourth of those achieved by wind energy.
23. See http://insideclimatenews.org/carbon-copy/03082015/did-epa-bulletproof-clean-power-plan-obama-climate-carbon-regulations.
24. See http://www.theenergycollective.com/jessejenkins/2266234/nuclear-retirements-would-sabotage-clean-power-plan-carbon-goal.
25. See http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today.
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38. See http://www.exeloncorp.com/PowerPlants/oystercreek/Pages/profile.aspx; and http://en.wikipedia.org/wiki/Oyster_Creek_Nuclear_Generating_Station.
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42. See http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Operating-Plant-Basic-Information.
43. Data on Byron and Quad Cities are from Michael Pacilio, COO of Exelon Generation.
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45. All capacity figures are from Nuclear Energy Institute (NEI), http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Operating-Plant-Basic-Information.
46. In May 2015, U.S. nuclear capacity was 98.7 gigawatts. See http://cpuc.ca.gov/NR/rdonlyres/B123F7A9-17BD-461E-AC34-973B906CAE8E/0/ExecutiveSummary33percentRPSImplementationAnalysis.pdf.
47. See http://www.nei.org/News-Media/Speeches/Sen-Lamar-Alexander,-"The-United-States-Without-Nu.
48. See http://csis.org/files/publication/130614_RestoringUSLeadershipNuclearEnergy_WEB.pdf.
49. The 75 TWh figure is based on a comparison of U.S. and global nuclear productivity. In 2013, U.S. reactors with capacity of roughly 100 gigawatts produced 789 TWh of electricity, or 7.89 TWh per gigawatt of capacity annually. See http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Nuclear-Energy-America-s-Low-Carbon-Electricity-Le. Globally, during 2005–14, nuclear productivity averaged 7.17 TWh per gigawatt of installed capacity.
50. NEI puts nuclear's contribution to U.S. zero-carbon electricity at 63 percent. Thus, each 10 percent reduction in nuclear capacity would result in a loss of about 6 percent of zero-carbon electricity production.
51. In 2014, U.S. solar production was 18 TWh of electricity, and wind-energy production was 183.6 TWh. See *BP 2015*.
52. In 2014, Germany produced 34.9 TWh of electricity from solar. Global production was 185.9 TWh. See *BP 2015*.
53. See http://www.wsj.com/articles/germanys-expensive-gamble-on-renewable-energy-1409106602.
54. See http://www.ft.com/intl/cms/s/0/02d594d8-29d8-11e4-914f-00144feabdc0.html#axzz3cyOLERvx.
55. During that period, Germany's rates rose from 20.2 eurocents to 29.7 eurocents. See http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do.
56. *BP 2015*.
57. Ibid.
58. Capacity data from *BP 2015*. Electricity cost data from Eurostat. In 2007, Spanish households paid 14 euro cents per kWh. In the second half of 2014, they paid 23.67 euro cents. http://elpais.com/elpais/2014/01/01/inenglish/1388590410_230748.html.
59. See http://ec.europa.eu/eurostat/statistics-explained/images/9/9c/Electricity_prices_for_household_consumers%2C_second_half_2014_%281%29_%28EUR_per_kWh%29_YB15.png. In March 2015, the average U.S. household was paying $0.123 per kWh; see http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.
60. See http://energy.gov/sites/prod/files/2013/12/f5/42864.pdf.
61. *BP 2015*.
62. See http://www.eia.gov/forecasts/aeo/pdf/tbla8.pdf.

63. *BP 2015*. During 2005–06, U.S. wind capacity increased by 3 gigawatts. Subsequent annual capacity increases to 2014 are as follows: 5, 8, 10, 5, 7, 13, 1, and 6 gigawatts.
64. See http://www.gallup.com/poll/182180/support-nuclear-energy.aspx.
65. See http://www.gallup.com/poll/182150/views-climate-change-stable-extreme-winter.aspx.
66. See http://www.southerncompany.com/about-us/our-business/southern-nuclear/pdfs/vogtleBrochure_2010.pdf.
67. See http://m.bizjournals.com/atlanta/blog/capitol_vision/2015/01/plant-vogtle-expansion-delayed-another-18-months.html?page=all&r=full.
68. See http://en.wikipedia.org/wiki/Prairie_State_Energy_Campus.
69. See http://union-bulletin.com/news/2014/jun/06/construction-starts-gas-fired-power-plant-boardman.
70. See http://en.wikipedia.org/wiki/Olkiluoto_Nuclear_Power_Plant.
71. See http://www.nytimes.com/2015/05/08/business/energy-environment/france-nuclear-energy-areva.html?_r=0.
72. See http://www.world-nuclear-news.org/NN-Flamanville-start-up-put-back-one-year-1911144.html.
73. The spot price on September 4, 2015, was $2.66. See http://www.bloomberg.com/energy.
74. *BP Statistical Review of World Energy 2014*.
75. See http://sinapse.ua/en/ge-jenbacher-cogeneration-plants-en/ge-jenbacher-9-en.
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77. See http://www.bloomberg.com/news/articles/2013-03-11/nuclear-industry-withers-in-u-s-as-wind-pummels-prices-energy.
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83. See http://www.wallstreetdaily.com/2015/03/14/electricity-sales-down; and http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_2.
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