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The incredible shrinking nuclear offset to climate change

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ABSTRACT
Can nuclear energy be much help when it comes to fighting climate change? Or have nuclear energy advocates greatly overstated their case? The likelihood that nuclear power will play a significant role in mitigating climate change is very low, absent a game-changing innovation that allows cheaper, safer nuclear power plants to come on-line much more quickly.

KEYWORDS
Nuclear energy; climate change; mitigation; greenhouse gas; emissions; nuclear power; renewable energy

On the margins of the last United Nations climate change conference, four eminent climate scientists made an impassioned plea for nuclear energy as the only viable path toward curbing global greenhouse gas emissions. One of them was former NASA scientist James Hansen, who was the first to tell the US Congress in 1988 about anthropogenically induced warming. Hansen and his colleagues Kerry Emmanuel, Ken Caldeira, and Ted Wigley told a Paris audience that it would be crazy not to use all the tools that humanity has to prevent climate change, and that there is no particular reason why society should favor renewable energy over other forms of abundant energy (World Nuclear News 2015).

As they explained in an accompanying OpEd in *The Guardian* on 3 December 2015:

> We have become so concerned about humanity's slow response to this challenge that we decided we must clearly set out what we see as the only viable path forward.… Nuclear power, particularly next-generation nuclear power with a closed fuel cycle (where spent fuel is reprocessed), is uniquely scalable, and environmentally advantageous. (Hansen et al. 2015)

Their proclamation, like the Paris Agreement, is probably too late to keep temperatures rising above 2°C. Nuclear energy has been struggling for a seat at the climate change banquet for years. It is not widely regarded as a form of renewable energy, and it has not won acceptance as a UN Clean Development Mechanism – the means by which developing countries can earn credits for their emissions reductions' projects. Nor is nuclear energy very prominent among countries' Intended Nationally Determined Contributions, where countries publicly outlined what post-2020 climate actions they intend to take under the new international agreement. Without these climate change "booster shots," nuclear energy can expect to continue ambling along at a growth trajectory of somewhere between 1 and 1.5% annually. In the context of high rates of electricity growth, this means that nuclear energy will decline in significance rather than grow.

The glaring contradiction between the rosy theoretical futures for nuclear energy and its reality is not really new. But contrary to all expectations, nuclear energy is becoming less – rather than more – relevant as the time frame for mitigating climate change becomes shorter. Ironically, the four climatologists concerned about humanity's slow response might have chosen the slowest path forward for producing clean energy. What's more, even if nuclear energy expansion could be accelerated, we might not like the outcome. As physicist Robert Socolow cautioned days before the 2015 Paris meeting: "Every 'solution' to climate change has a dark side that makes it dangerous" (Socolow 2015).

The climate change challenge

The concentration of so-called greenhouse gases – carbon dioxide (CO_2), water vapor, ozone, nitrous oxide, chlorofluorocarbons, and methane – in the atmosphere has risen dramatically since preindustrial times. Levels of carbon dioxide alone have risen 43%, from about 280 parts per million (ppm) in preindustrial times to 401 ppm today. In the last 40 years alone, annual CO_2 emissions have doubled and reached a high of 35.9 billion metric tons (gigatonnes, or Gt) in 2014. Although emissions stopped climbing for the first time in 2015, this doesn't mean that they have truly peaked. For example, China, the largest emitter of carbon, was planning on 2030 as its peak emissions

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year (but agreed last year to pursue more aggressive reductions).

Since the United Nations initiated its annual climate change conferences more than 20 years ago, countries have debated the scientific basis and extent of the problem, mitigation measures, and who should pay. In Cancun in 2010, countries agreed to seek to stabilize greenhouse gas emissions to limit the rise in global temperatures to below 2°C. By 2014, however, mitigation experts concluded that those pledges from Cancun were at least as likely to still result in a rise of 3°C, or well above the level at which climate change is inevitable – with its attendant rise in sea levels, changes in rainfall patterns, mass migrations, loss of species, and other severe disruptions. Last year in Paris, countries reiterated their intent to limit the average global temperature to less than 2°C and to make every effort to limit it to 1.5°C. UN experts concluded that this will require lowering greenhouse gas emissions by "40 to 70% compared with 2010 by mid-century, and to near-zero by the end of this century. Ambitious mitigation may even require removing carbon dioxide from the atmosphere." (IPCC Press Release 2014).

Figure 1 shows how soon emissions would have to peak to limit global average temperature changes. In addition to drastically reducing carbon emissions, the world would also have to take CO_2 out of the atmosphere by a combination of measures – for example, through carbon sequestration, and allowing more trees to absorb carbon. Although carbon capture facilities may be necessary, challenges there are also significant. Even limited impact on reducing the CO_2 in the atmosphere through carbon capture, according to one estimate, would require completing one carbon capture facility every working day for approximately the next 70 years (Skuce 2016).

There is no question that the more ambitious goals place a premium on efficiency and speed. According to the International Energy Agency (IEA), measures to improve energy efficiency are "the cheapest and fastest way to curb demand and emissions growth in the near term," and most of the IEA's scenarios for slowing the growth of carbon emissions rely heavily on efficiency improvements.

James Hansen and his colleagues have warned that "[t]hrowing tools such as nuclear out of the box constrains humanity's options and makes climate mitigation more likely to fail." Still, public policy planners know that resources are not infinite and that it might be best to work smarter, not harder. The biggest question is whether nuclear energy, at this point in time, can truly generate a significant impact on climate change.

A significant impact

Decarbonizing electricity production is, to quote US Energy Secretary Ernest Moniz, "the lead horse in the climate race" (Moniz 2016). Electricity generation emits 41% of the world's energy-related carbon dioxide because it is dependent on fossil fuels. More than 60% of electricity production uses coal and natural gas. Renewable energy (approximately 22%), nuclear energy (10%), and petroleum and other liquid fuels (5%) round out the rest of the electricity supply (EIA 2016). Most mitigation scenarios feature decarbonizing the electricity supply, and computational models assume that it can be achieved faster than decarbonizing other sectors like industry, buildings, and transportation (IPCC 2014). By 2040, the International Energy Agency predicts that the electricity supply will be somewhat evenly divided between coal, natural gas, and renewables, each at somewhere between 28 and 29%.

There is no doubt that nuclear power could be an asset for decarbonization: Reactors operate at relatively high capacity factors with mostly predictable outages; they do not emit CO_2; and they have low life-cycle CO_2 emissions – comparable to renewable energy. (One estimate is that nuclear power emits 5 grams per kilowatt-hour compared to a coal plant's 900 grams per kilowatt-hour.) (Technical

CO2 concentration level (PPM)	CO2 equivalent concentration level (PPM)	Global mean temperature > pre-industrial levels	Peaking year for emissions	Global change in emissions in 2050 (as % of 2000 levels)
350–400	445–490	2.0–2.4° C	2000–2015	-50 – -85%
400–440	490–535	2.4–2.8° C	2000–2020	-30 – -60%
440–485	535–590	2.8–3.2° C	2010–2030	+5 – -30%
485–570	590–710	3.2–4.0° C	2020–2060	+10 – +60%

Source: Intergovernmental Panel on Climate Change, 2007. PPM: Parts Per Million

Figure 1. Carbon dioxide concentration levels and temperature rises.

Report for British Energy 2005) Still, the high construction costs of nuclear power plants relative to other electricity generation options present an obstacle to widespread deployment, as does the time required – generally 10 years – from licensing to operation.

A simple way to calculate nuclear energy's impact on carbon emissions savings uses a general rule of thumb. A 1-Gigawatt-electric (GWe) nuclear power plant operating at 90% of capacity would save the emission of 1.5 million metric tons of carbon annually, assuming that it is built in place of a modern coal electric plant (Global Fissile Material Report 2007). If it replaced a gas plant, the carbon savings would be about half that. (Displacing renewables would have no impact. Often, nuclear energy is not depicted as competing with renewables because wind and solar energy are intermittent and hydropower is seasonal. But as intermittent energy sources are combined with storage innovations, this risk of displacement could become real.)

Right now, natural gas and renewables are replacing coal plants in Europe (EIA 2016). But a big push to replace coal with nuclear power could impose significant delays and expense, displacing quicker, cheaper renewable sources of energy. The Intergovernmental Panel on Climate Change mitigation working group cautioned in 2014 that "well-designed system and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors." Choices regarding size (large or small) and type (centralized or distributed) of generation facilities will affect the extent to which nuclear energy might displace other low-carbon options. This is important because smaller, distributed electricity generation may be a more favorable option for developing countries, where 70% of the projected growth in electricity demand is expected by 2050.

Scenarios for bigger nuclear energy impact

Most of the scenarios in which nuclear energy makes a significant contribution to climate change mitigation envision the large-scale deployment of new nuclear power plants. For example, MIT's 2003 study, *The Future of Nuclear Energy*, featured a high-growth scenario for nuclear energy with almost five times as many reactors as then in operation. More recently, James Hansen suggested that nuclear energy could replace all fossil fuel electricity by 2050 if the industry built 61 reactors per year. That total – 2,135 reactors in 35 years – dwarfs the 667 reactors that have been built in the 60 years since nuclear power reactors were first connected to the grid (450 operating now, 60 under construction, 157 decommissioned). It could also cost close to $10 trillion, based on an estimate of $1.5 trillion for 300 reactors (Hinze 2016).

Perhaps the scenario that has most captured the public's imagination is the "wedge" analysis published a dozen years ago by Princeton University professors Stephen Pacala and Robert Socolow in *Science*. Their aim was to show how different combinations of eight existing technologies, or wedges – such as increased efficiency, solar power, or replacing all of our coal-fired electric plants with natural gas, to name three of them – could be used to help stabilize emissions for the next 50 years, without compromising economic growth (Socolow and Pacala 2004) (See Figure 2).

This analysis of daunting but do-able strategies included nuclear energy, although the authors acknowledged that nuclear energy was probably the most controversial of all the wedge strategies (Socolow and Pacala 2006). The challenge to save 25 billion tons of carbon over 50 years meant adding twice the number of nuclear power plants to the existing fleet, or nearly 700 reactors worldwide. Over 50 years, the nuclear industry would have to steadily build 14 new reactors per year. (In 2004, 440 reactors operated, with a capacity of 365 GWe. Doubling the capacity would mean adding 730 GWe.) This calculation assumed that all existing reactors would continue to operate in 2050, but of course most of them would need to be replaced. In 2004, this would have meant building 23 large reactors per year, for a total of 1,095 GWe constructed by 2050. Today, because nuclear power has barely maintained its capacity, more than 40 reactors would have to be built per year to achieve the nuclear wedge. This assumes that 73% of the fleet that will be older than 60 years in 2050 will have to be replaced.

In contrast, the scenarios produced by the IEA tend to feature less ambitious goals for nuclear energy in climate mitigation. In 2008, one of the most aggressive scenarios for climate change mitigation in the IEA's *Energy Technology Perspectives* – the Blue Scenario – sought to halve emissions by 2050. With a yearly construction rate of 32 new nuclear power plants to 2050, nuclear energy contributed just 6% to total CO_2 emission reductions, while producing 24% of global electricity. To give an idea of scale, the following all produced greater carbon savings: increased end-use fuel efficiency (24%), renewables (21%), end-use electricity efficiency (12%), end-use fuel switching (11%), carbon capture and storage (CCS) power generation (10%), CCS industry transformation (9%), and power generation efficiency and fuel switching (7%).

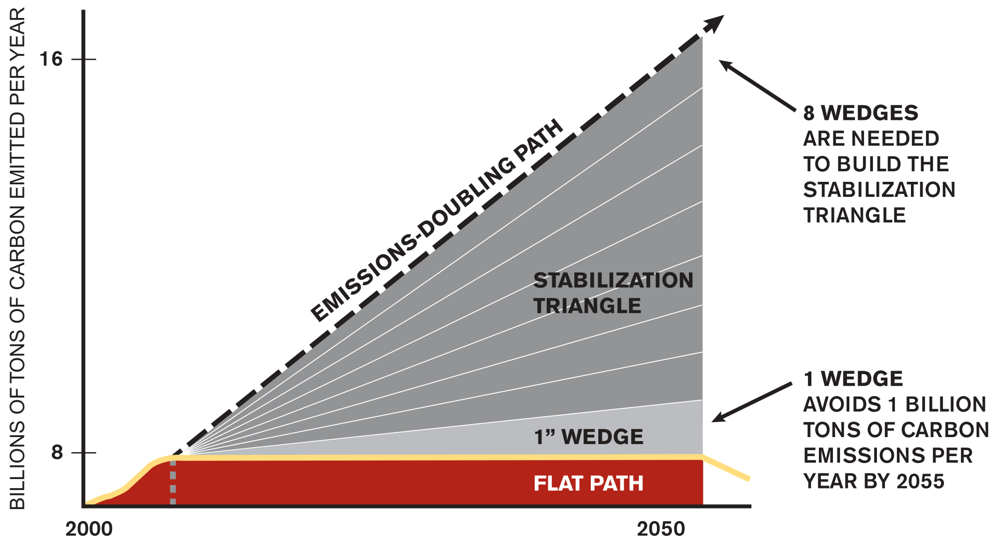

Image courtesy of Carbon Mitigation Initiative, Princeton University.

Figure 2. Wedge analysis.

Although other IEA scenarios show even more ambitious growth for nuclear energy, the expectations for nuclear energy never get above 6 or 7% of CO_2 reductions. For example, the IEA's 2016 Two-Degree Scenario requires building more than 22 big nuclear power plants each year that would still only provide just 7% of cumulative emissions reductions by 2050. Under this scenario, greater end-use fuel and electricity efficiency provided 38% of reductions, renewables provided 32%, and CCS accounted for 12% of reductions.

What has really changed over time, at least in the IEA's scenarios, is that renewable energy is now regarded as capable of contributing much more, from 21% in the 2008 scenarios to 32% in the 2016 scenarios. This reflects actual growth in capacity. In 2014 alone, global electricity generation increased nearly 121 GWe, with 30 GWe from hydropower, 40 GWe from solar, and 51 GWe from wind. In 2015, more than half of all new electricity generated came from renewable energy (147 GWe). And since 2000, power grids have added 417 GWe of wind energy and 229 GWe of solar energy (Schneider and Froggatt 2016.).

Even China's ambitious nuclear power plant construction, which is the envy of the global industry, is dwarfed by China's accomplishments in the renewables sector. In 2015, China led global investment in renewable energy, pouring about $100 billion annually into that sector, compared to the $18 billion it spent on nuclear reactor investments (IEA 2016a). In 2015, China added 32.5 GWe of wind capacity and 18.3 GWe of solar capacity, compared to 6 GWe of added nuclear capacity.

Worldwide, renewables are capturing larger shares of the electricity market. In 2015, solar-sourced electricity grew 33%, and wind-sourced electricity grew 17%. Nuclear-sourced electricity, on the other hand, grew only 1.3%. According to the IEA, global investment in all renewables was about $280 billion, more than covering the 2015 global electricity growth (IEA 2016b). Of course, solar and wind need to grow at continued high rates to catch up to nuclear energy's output, but the trend line is unmistakable.

What's really happening in nuclear energy

About 10 years ago, concerns about climate change, energy security, and rising electricity demand fueled a resurgence of interest in nuclear energy. At that time, 30 countries (plus Taiwan) generated about 16% of global electricity from nuclear power. A renaissance of growth in those countries might have achieved significant gains for nuclear energy, but the real story for nuclear energy mirrors electricity demand: growth in Asia, with declines forecast in Europe and the United States (EIA 2016). Today, nuclear energy generates only 10% of global electricity, and it will struggle to keep that market share for several reasons.

First, the top six countries producing 70% of nuclear energy a few years ago have failed to generate a renaissance in their own countries. In Europe, Germany will phase out nuclear energy by 2022, while France passed a law in 2014 to reduce reliance on nuclear energy from 75% of its electricity to 50% by 2025. Switzerland and Belgium are also poised to close their nuclear reactors.

The world leader in nuclear energy – the United States – virtually stopped building reactors in the late 1970s in response to escalating costs and a nascent environmental movement. More recent efforts to jump-start new nuclear construction in the United States (e.g. through programs like Nuclear Energy 2010) have produced anemic results rather than a true revitalization. Today, the United States has four power reactors under construction out of a fleet of 100, with an average age of 35 years. Some reactors, despite 20-year extensions of their operating licenses, have been shut down because they were not cost-effective to operate. The federal Clean Power Plan failed to provide incentives for extending licenses for existing US nuclear power plants.

Japan was also one of the top nuclear energy producers. The 2011 accident at Fukushima Daiichi power plant slowed down worldwide construction while the industry paused to take stock. The fact that most of Japan's reactors are still awaiting authorization to restart accounts for some of the decline in nuclear electricity since 2011.

This means that the United States, France, Russia, China, and South Korea produced about two-thirds of global nuclear electricity in 2015. China is the obvious bright spot in that group. The US Energy Information Administration outlook to 2040 predicts that "virtually all the projected net expansion in the world's installed nuclear power capacity occurs in the non-OECD [Organization of Economic Cooperation and Development] region, led by China's addition of 139 GWe from 2012–2040." China has announced its intention to double nuclear energy from 26 to 58 GWe by 2021 and ramp up to 150 GWe by 2030.

A big question is whether this new capacity in China can offset the declines in North America and Europe. From 2000 to 2015, new construction added almost 10% more nuclear energy capacity. But total electricity generation had increased by 60% in that time period. The fact that Japan's reactors eventually all came off-line in the wake of the Fukushima accident contributed to an actual decline in electricity production over that time (IAEA 2016). Even if those reactors were operating, however, nuclear's share would not have reached more than 11% of electricity production. For now, growth in nuclear energy is nowhere near that of electricity demand, which is expected to double by 2050. This is a second reason that nuclear energy will lose market share – its growth rate is magnitudes smaller than growth in electricity demand.

Another challenge for market share is simply that the decline in nuclear power plant construction in the last 20 years has left an aging fleet of nuclear reactors; by 2050, three-quarters of the fleet will be 60 years or older. Figure 3 highlights the need for replacements beginning in 2030. Assuming that countries decide to extend the lives of their reactors to 60 years, it will still be necessary to replace at least 331 nuclear power plants by 2050. Replacing those power reactors alone

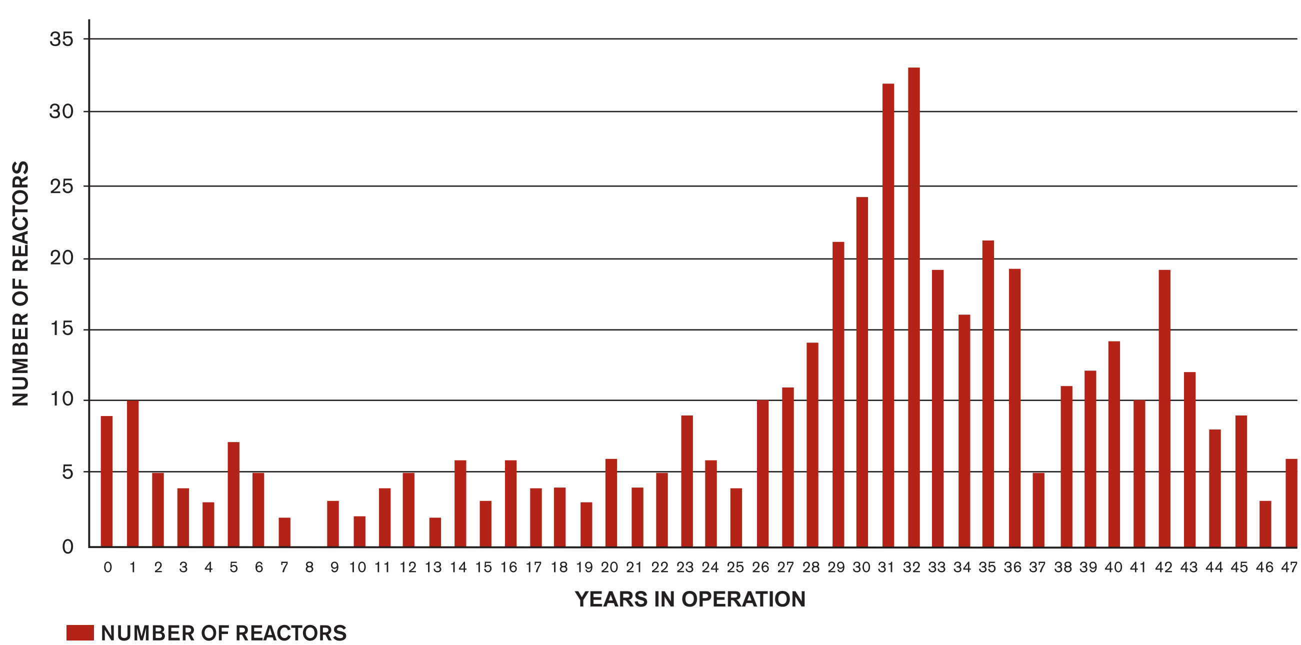

Figure 3. Age distribution of currently operating commercial nuclear power reactors.
Source: Data from Power Reactor Information System (PRIS), International Atomic Energy Agency.

will require a completion rate (that is, connection to the electricity grid) of eight per year on top of the new construction to mitigate climate change.

Analysts point to the boom years of nuclear energy as a guide for what is possible in terms of ramping up nuclear energy construction in the future. At the height of nuclear power expansion in the 1980s, it was possible to connect 33 reactors to the grid in both 1984 and 1985. During the biggest decade of growth (from 1976 to 1985), an average of 22 reactors was connected to the grid each year. Over the entire history of nuclear power plant construction, the average annual number of plants connected to the grid was 11 per year. And in the last 10 years, only five reactors have been connected, on average, to the grid each year.

This calls into question the ability of the nuclear industry to quickly ramp up construction. Ten years ago, there were well-known shortfalls of capacity in important areas like ultra-heavy forgings (preferred for larger, modern reactors), large manufactured components, engineering, and skilled construction labor. Since then, countries have invested in ultra-heavy forging, and a decline in orders after Fukushima eliminated potential bottlenecks. For example, Japan Steel Works doubled its capacity from 6 to 12 ultra-heavy forging sets per year. China also increased its capacity from 12.5 to 16, and so did Russia.

Overall, however, the capability to produce safety-related components and systems in Europe and North America has declined while capabilities in emerging industrial countries may not yet meet expected industry requirements (World Nuclear Association 2016). In addition to the major reactor vendors, the supporting industries lower down in the supply chain are also critical to the effort. They must be capable of producing nuclear-quality components and materials. In the United States, the number of firms engaged in such highly specialized work is a little more than half of what it was in the 1980s.

A final factor is scarcity of labor. According to the Nuclear Energy Institute, 39% of the nuclear industry labor force in the United States will be eligible for retirement in 2018 (Nuclear Energy Institute 2015). It is not just a question of reactor operators, but the kinds of skilled craftsmen (such as welders) required for nuclear construction. Building a nuclear power plant in the United States requires 1,400–2,300 construction workers for four or more years, and the permanent labor force of a nuclear power plant numbers between 400 and 500. The ability to attract, train, and maintain sufficient labor is a recurring theme in several key nuclear power countries, including the United States, Japan, France, and China.

Finally, the length of construction is a critical element in the cost-effectiveness of nuclear power. The availability of robust manufacturing capabilities is a prerequisite for – but not a predictor of – timely completion. Reactors under construction now appear to be taking longer to complete than they did in the 1970s and 1980s. Sixty reactors are now under construction worldwide, with delays in construction experienced by two-thirds of them. Construction starts date back as far as 1983, but the average time under construction has been 6.2 years (Schneider and Froggatt 2016). At least four are unlikely to be completed by 2020: two in Japan and two in Ukraine. Worldwide, few reactors that are not already in the licensing process or under construction could be operational before 2030.

Looking back on the wedge analysis, the challenges for all the technologies seemed fairly daunting, at least in terms of practicality, affordability, scalability, and quick deployment. Some of the options included halving the use of 2 billion cars worldwide, increasing the fuel efficiency of cars to 60 miles per gallon, and increasing solar photovoltaic cell capacity 700-fold. In the dozen years that have elapsed since the wedge analysis was published, some of the wedges now appear to be feasible. For example, the goal for solar photovoltaic energy was 2,000 GWe peak generation by 2054. In 2012, peak capacity reached 100 GWe and by 2016, it had grown to 233 GWe. Since new capacity is being added at about 60 GWe per year (although production is slowing), a solar PV wedge looks quite possible by 2050. According to the IEA, solar photovoltaic, on-shore wind, and electric vehicles are the only clean energy deployments that are on track for meeting the 2-degree scenario. A handful of others, including nuclear, will require accelerated improvement, while more efficient coal-fired power, CCS, biofuels, and buildings are not on track (IEA 2016b).

What of the nuclear wedge? For nuclear energy, a challenge that was daunting in 2004 seems even more daunting today, because nuclear energy has actually declined in the last decade. If nuclear had been on track for meeting the requirements of its wedge, capacity today would have risen to about 540 GWe (at the lower end) on the way to 1,095 GWe by 2050. Nuclear is clearly behind the curve.

The prospects for acceleration

The Paris Agreement places a premium on practicality, affordability, scalability, and quick deployment.

Nuclear energy has definite advantages in scalability, leading enthusiasts to claim that nuclear is the only technology capable of providing carbon-free power on the scale required by modern civilization. Renewables tend to be treated as side dishes to nuclear energy's main course. For example, last year at the Paris Climate Conference, MIT climate professor Kerry Emmanuel told delegates: "The numbers don't add up unless you put nuclear power in the middle" (World Nuclear News 2015).

But the size and complexity of reactors can add to the time required to build them and the infrastructure to support them. Nuclear energy has the highest lead time (at least in the United States) of any power generation source: six years, compared to two years for solar photovoltaic and conventional and advanced combustion turbine; three years for wind, solar thermal, fuel cells, and combined cycle plants; and four years for new coal plants with CCS (EIA 2016).

The ability of nuclear energy power plants to provide a lot of electricity per unit is offset by the limits of the industry itself to build many power plants at the same time. Expansion in the supply chain is pegged to demand, yet some prominent orders have been delayed or cancelled in the past few years (e.g. reactors in Vietnam). When advocates of nuclear power talk about nuclear energy's scalability, they assume that nuclear construction can expand well beyond its historic high-water marks. While faster deployment might be possible in countries that have experience with nuclear energy, have existing sites and infrastructure, and have public support and manufacturing infrastructure, the current growth pattern for nuclear energy is expansion into *new* markets, in Asia and the Middle East. The shift in nuclear energy construction from Europe to Asia and from more advanced to less advanced economies mirrors the shift in electricity supply and demand.

For many of the lesser developed countries, adding nuclear energy in time to meet rising demand would be challenging. And for some (like Singapore, Taiwan, Indonesia, and several countries in Africa), it may not be a viable option. China may be the exception to this rule. As for India – the world's fourth largest emitter of carbon dioxide – its ambitious targets for nuclear energy have never been met. Although some observers thought that opening up international nuclear trade to India through its 2008 exemption from the Nuclear Suppliers Group guidelines would flood the country with foreign reactors and fuel, growth in foreign reactors has been slow. At present, India's 22 operating reactors provide 5.3 GWe capacity. Five additional reactors are under construction and should be operational by 2020. They will, however, add only 3.3 GWe capacity for a total of 8.6 GWe. India's current plans reportedly entail increasing nuclear energy's 3% share of electricity generation to 5% in 2020, 12% in 2030, and 25% in 2050. Short-term goals have been repeatedly scaled back, while longer term goals remain immutable. It is hard to see how India will build hundreds of reactors by 2050 to meet its 25% of the predicted 1,095 GWe of required baseload electricity worldwide (IEA 2015).

Challenges and risks to overcome

In 2009, Socolow updated his thinking on nuclear power in an article co-authored with Princeton colleague Alexander Glaser. Stating that the next decade would be critical for nuclear power, the authors suggested that while other technologies were ready for deployment, nuclear energy would have to spend the next decade establishing adequate technologies and new norms of governance. In their view, nuclear power needed to solve issues related to capital and operating costs, safety records (note that this was before Fukushima), coupling to nuclear militarization, and "the overall sense of competence and responsibility that the industry projects" (Socolow and Glaser 2009).

Capital costs continue to be challenging for nuclear energy, although some observers suggest that they are similar to those for wind and solar when adjusted for capacity factors. Small modular reactors, which seemed to be the industry's answer to lowering capital costs, have not advanced significantly toward wide-scale operational capability. In the United States, at least, licensing is proceeding slowly.

In the wake of Fukushima, many countries paused to conduct stress tests of existing reactors, revisited emergency power requirements for reactors, slowed down planned construction, and worked to enhance, in some cases, the independence of nuclear regulators. And there is no question that the tragedy at Fukushima dealt a blow to public confidence regarding nuclear power in some countries. More attention to nuclear regulation since then has illuminated some shortcomings in a few countries, including South Korea's 2013 scandal involving forgeries of safety certifications and more recently, accidents at Belarus' Ostrovets construction site (Choe 2013).

The risks that peaceful nuclear energy will be diverted for military uses (so-called nuclear militarization) are generally perceived as a problem related to the spread of nuclear fuel cycle capabilities rather than nuclear power reactors. In many cases, however, nuclear power plans offer an excuse for acquiring fuel cycle capabilities. Since the Nuclear Nonproliferation Treaty does not contain any limits on fuel cycle capabilities, countries are legally free to acquire sensitive technologies if they can find a vendor willing to supply them. After 70 years, despite dozens of proposals, the international community has failed to agree on any significant limits on countries acquiring sensitive fuel cycle capabilities beyond voluntary supplier controls (Squassoni 2009; Squassoni et al. 2015).

Iran has aptly demonstrated what happens in the absence of legally binding limits on sensitive technologies: Despite multiple violations of its safeguards obligations over decades, Iran succeeded in retaining its right to some fuel cycle capabilities. Nonetheless, the 2015 agreement reached with Iran, known as the Joint Comprehensive Plan of Action, is a step forward in recognizing and demonstrating that nuclear activities that are ostensibly in the domain of peaceful nuclear energy – such as uranium enrichment, medical radioisotope production, and nuclear research reactors – need to be monitored more closely for their military potential. Iran agreed to far more extensive limits and monitoring under the deal than would have been required as a member in good standing of the Nuclear Non-Proliferation Treaty.

The need for additional restrictions like limits on stockpiles of enriched uranium and limits on levels of enrichment, as illustrated by the case of Iran, raises questions about the efficacy of the nonproliferation regime. It is not at all certain that those kinds of limits could be more widely applied in the nonproliferation regime. But, a major expansion of nuclear energy in Asia, the Middle East, and Africa could pose significant risks without those assurances.

Ultimately, what separates nuclear energy from other forms of electricity generation is its military potential. In addition to concerns about nuclear weapons proliferation, the potential for sabotage by terrorist groups is also a real threat. Wider geographic dispersion could exacerbate both of those risks. Although all electricity systems may be vulnerable to infrastructure attacks in regions of uncertain political governance, the consequences of sabotage of nuclear power plants could be devastating.

A climate cure worse than the disease

On the surface, there are good reasons to support nuclear energy to mitigate climate change. Nuclear power plants can produce large amounts of electricity on a steady, predictable basis; they have low life cycle carbon dioxide emissions comparable to renewables such as wind power, photovoltaics, and biofuels; and nuclear energy is a proven technology. In the last 10 years, however, the climate change incentive for a big expansion of nuclear energy has become less compelling. The timeline for deep decarbonization is no longer measured in decades, but in years.

Contrary to some assertions, the numbers don't work out for nuclear. Absent a major breakthrough in cost or manufacturing capability, nuclear energy just cannot be expanded quickly enough to make a significant difference. Using the most optimistic of assumptions, completing every reactor under construction now by 2020 would add 59 GWe. Assuming the historic capability of connecting 11 reactors annually to the grid, the world will be able to increase nuclear capacity by about 20% over 34 years. This is nowhere close to what would be needed for a significant contribution. Doubling that production rate, under the most current IEA Two-Degree Scenario, would allow nuclear energy to contribute to just 7% of the required carbon dioxide emission reductions by 2050.

Part of the problem lies in the fact that although the scale of climate change is global, decisions about energy are still largely local. The Paris Agreement on climate change is a bottom-up treaty that requires countries to submit nationally determined plans for collectively reducing their greenhouse gas emissions by 50% by 2050. So far, nuclear energy hasn't figured very prominently in those reports. According to one tally, of the 163 reports already submitted, only 11 mention nuclear power (Schneider and Froggatt 2016.). Of those 11, 6 mention expanding nuclear energy to meet climate change goals. These are the reports submitted by Belarus, China, India, Japan, Turkey, and the United Arab Emirates. Three of those countries – Belarus, UAE, and Turkey – will be first-time operators of nuclear power plants. Belarus' nuclear power plant construction has been plagued by accidents, including dropping a reactor vessel, and three deaths. Turkey's Akkuyu project slowed down last year in response to poorer Turkish–Russian relations. Japan is obviously seeking to increase the electricity from nuclear energy, but it will be a slow, uphill struggle if the last five years provide any guide.

China and India are obviously more important in the overall landscape of nuclear energy and climate change, because they are such large emitters of CO_2 and have forecast such large electricity growth. Together, they might build close to 180 GWe of new nuclear capacity by 2050. For both, however, efficiency will play a much larger role in bringing down their carbon emissions.

The stark contrast between modest individual country plans regarding nuclear energy and how advocates of nuclear energy envision its growth is nothing new. Nuclear energy has always promised more than it has delivered. In the case of climate change, countries' unwillingness to accept top-down approaches to decarbonizing electricity supply very likely means that nuclear energy will not feature prominently in efforts to halt growth in greenhouse gas emissions. This is not necessarily a bad thing, if it buys time to address in a more meaningful way the traditional cost, safety, security, waste, and proliferation challenges that nuclear energy poses. After all, there is little reason to pursue a climate cure that could turn out to be worse than the disease.

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