*Should Nuclear Energy Play a Role in a Carbon-Constrained World?*

# Should Nuclear Energy Play a Role in a Carbon-Constrained World?

J. Buongiorno[*1], M. Corradini[2], J. Parsons[1], D. Petti[3,1]
[1] Massachusetts Institute of Technology (MIT)
[2] University of Wisconsin at Madison
[3] Idaho National Laboratory (INL)
[*] jacopo@mit.edu , +1(617)253-7316

## Abstract

We summarize the findings of a new MIT study on the future of nuclear energy. The context for the study is the challenge of simultaneously expanding energy access and economic opportunity to billions of people while drastically reducing emissions of greenhouse gases. We find that while decarbonization of the electricity sector can be accomplished employing an assortment of low-carbon technologies in various combinations, nuclear has a uniquely valuable role to play as a dispatchable low-carbon technology. Excluding a dispatchable low-carbon option like nuclear, as the German Energiewende does, significantly increases the cost and difficulty of achieving decarbonization targets. We also find that the high cost of new nuclear plants limits nuclear's role in a balanced portfolio. Reducing this cost can significantly reduce the total cost of decarbonization. Our study identified the factors driving up cost, and we identify promising approaches to achieving cost reductions. Finally, we identify needed government policies. These include decarbonization strategies that recognize the contribution of all low-carbon energy technologies and treat them equally in the electricity market. These also include policies to accommodate and support development and demonstration of advanced reactor designs.

**Keywords:** nuclear, carbon emissions, greenhouse gases, construction costs, energy policy

## The Big Picture

Access to electricity plays a vital role in improving standards of living, education, and health. This relationship is illustrated by Figure 1, which locates various countries according to their score on the Human Development Index, a well-known metric of economic and social development, and per capita electricity use. As countries develop, electricity use tends to rise; according to current forecasts, electricity consumption in developing non-OECD (Organisation for Economic Co-operation and Development) countries is expected to grow 60% by 2040, whereas worldwide use is expected to grow 45% in the same timeframe (U.S. Energy Information Agency, 2017).

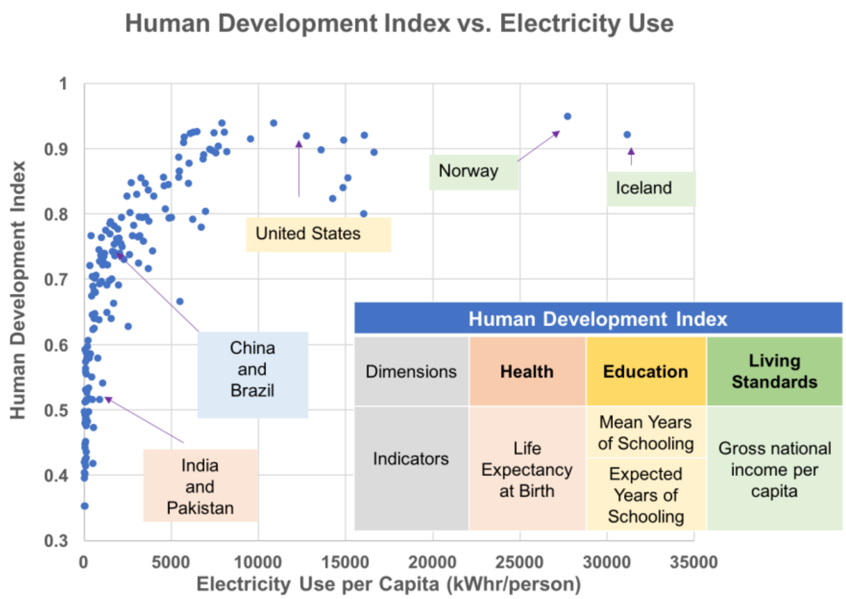


**Figure 1.** Human Development Index versus per capita electricity consumption for different countries (United Nations Development Programme, 2017)

Expanding access to energy while at the same time drastically reducing the emissions of greenhouse gases that cause global warming and climate change is among the central challenges confronting humankind in the 21$^{st}$ century. This study focuses on the electric power sector, which has been identified as an early target for deep decarbonization. In the foreseeable future, electricity will continue to come primarily from a mix of fossil fuels, hydropower, variable renewables such as solar and wind, and nuclear energy (U.S. Energy Information Agency, 2017). At present nuclear energy supplies about 11% of the world's electricity and constitutes a major fraction of all low-carbon electricity generation in the United States, Europe, and globally (Figure 2). Nuclear energy's future role, however, is highly uncertain for several reasons: chiefly, escalating costs and, to a lesser extent, the persistence of historical challenges such as spent fuel disposal and concerns about nuclear plant safety and nuclear weapons proliferation.

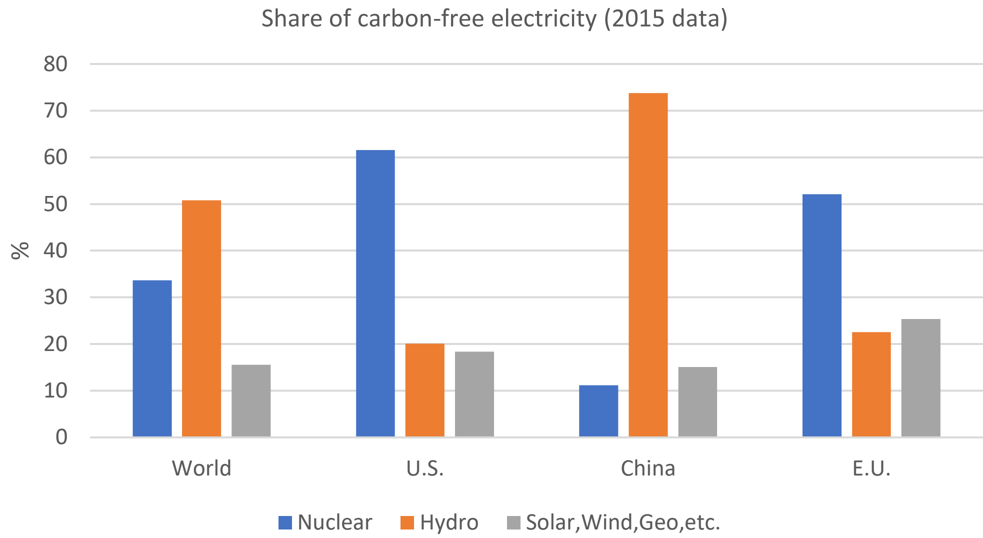


**Figure 2.** Share of carbon-free electricity sources in several major economies and worldwide (International Energy Agency, 2017)

## The Nuclear Energy Landscape

Since MIT published its first *Future of Nuclear Power* study (Deutch, et al., 2003), the context for nuclear energy in the United States and globally has changed dramatically. Throughout most of the 2000s, the U.S. fleet of nuclear power plants was highly profitable: their capital costs had been largely amortized over previous decades and their production costs were low compared to the relatively high cost of fossil and renewable alternatives. As utilities sought to maximize the value of their nuclear assets, they embarked on a flurry of market-driven nuclear power plant purchases, power uprates, and license extensions. The situation changed quickly after 2007, as large quantities of inexpensive shale natural gas became available in the United States and the Great Recession depressed electricity demand and prices. Since then, nuclear power plants in the United States have become steadily less profitable and the industry has witnessed a wave of plant closures. Two recent examples include the Kewaunee plant in Wisconsin, which shut down in 2013 (Dotson, 2014), and the Fort Calhoun plant in Nebraska, which shut down in 2016 (Larson, A., 2016). Both plants shut down because they could not compete with cheaper generation options. Similarly, falling natural gas prices in Europe and Asia have put more economic pressure on nuclear power in those regions also.

While the U.S. nuclear industry remains exceptionally proficient at operating the existing fleet of power plants, its handling of complex nuclear construction projects has been abysmal, as exemplified by the mismanagement of component-replacement projects at the San Onofre (Mufson, 2013) and Crystal River (Penn, 2013) plants, which led to the premature closure of both plants in 2013. Other projects, including the troubled Vogtle (Proctor, D., 2017) and V. C. Summer (Downey, 2017) expansion projects, have experienced soaring costs and lengthy schedule delays. In the case of Vogtle and V.C. Summer, costs doubled and construction time increased by more than three years, causing the reactor supplier Westinghouse (Cardwell & Soble, 2017) to declare bankruptcy (Westinghouse only began emerging from Chapter 11 protection in 2018) (Hals & DiNapoli, 2018). The V. C. Summer project was ultimately abandoned in 2017 (Plumer, 2017).

New nuclear plant construction projects by French reactor suppliers Areva and EDF at Olkiluoto (Finland) (Rosendahl & Forsell, 2017), Flamanville (France) (Reuters, 2018), and Hinkley Point C (United Kingdom) (BBC News, 2017), have suffered similarly severe cost escalation and delays. Clearly, the goal of deploying new nuclear power plants at an overnight capital cost of less than $2,000 per electric kilowatt, as claimed by the North American and European nuclear industries in the 2000s (Winters, Corletti, & Thompson, 2001) (The Economics of Nuclear Power, 2008), turned out to be completely unrealistic. New nuclear plant construction (International Atomic Energy Agency, 2017) has continued at a steady rate in countries like South Korea, China, and Russia; construction has also recently started in the Middle East. Many of these projects have been completed more or less on time, and likely at significantly lower cost than comparable projects in the West, although it is often challenging to independently validate the cost figures published in these countries.

In 2011, the combined effects of a massive earthquake and tsunami triggered an accident at the Fukushima Daiichi nuclear power plant in Japan and led to an unfortunate decision by Japanese authorities to force the evacuation of nearly 200,000 people from the region surrounding the site. This event renewed public concerns about the safety of nuclear installations. Although the radiological consequences of the accident have been minimal (United Nations Scientific Committee on the Effects of Atomic Radiation, 2017), by 2012 the entire nuclear fleet in Japan was temporarily shut down, and only a handful of nuclear plants are currently back online in that country. In the wake of Fukushima, five countries (Germany, Switzerland, Belgium, Taiwan, and South Korea) (World Nuclear Association, 2017) announced their intention to ultimately phase out nuclear energy, though to date only Germany has taken immediate action toward actually implementing this policy.

Against this bleak backdrop, some opportunities have nonetheless emerged for the nuclear energy industry. Heightened awareness of the social, economic, and environmental risks of climate change and air pollution has provided a powerful argument for maintaining and potentially increasing nuclear energy's share of the global energy mix (Hansen, Emanuel, Caldeira, & Wigley, 2015). Private investors appear interested in developing and deploying advanced reactor technologies (Brinton, 2015), defined here as light-water-cooled small modular reactors (SMRs) and non-water-cooled reactors (Generation-IV systems), even as the readiness of these technologies has significantly increased in the past 15 years (ANL-INL-ORNL, 2016) (Generation-IV International Forum, 2014). Finally, there seems to be bipartisan support in the U.S. Congress for renewed American leadership in commercializing new nuclear technology (115th U.S. Congress, 2017-2018).

## The New MIT Study

In light of the important changes that have occurred in the past 15 years, coupled with the existential challenges that now confront the nuclear industry, we concluded that it was time to conduct a new interdisciplinary study analyzing the future prospects of nuclear energy in the U.S. and internationally. The objective of this paper is to summarize the key findings of the study. The reader is encouraged to examine the full study report (Buongiorno & al., 2018) for a detailed discussion and justification of the findings.

We have examined the challenge of drastically reducing emissions of greenhouse gases in the electricity sector, which has been widely identified as an early candidate for deep decarbonization. In most regions, serving projected electricity demand in 2050 while simultaneously reducing emissions will require a mix of electrical generation assets that is different from the current system. While a variety of low- or zero-carbon technologies can be employed in various combinations, our analysis shows the potential contribution nuclear can make as a dispatchable low-carbon technology. Without that contribution, the cost of achieving deep decarbonization targets increases significantly (see Figure 3, left column). The least-cost portfolios include an important share for nuclear, the magnitude of which significantly grows as the cost of nuclear drops (Figure 3, right column).

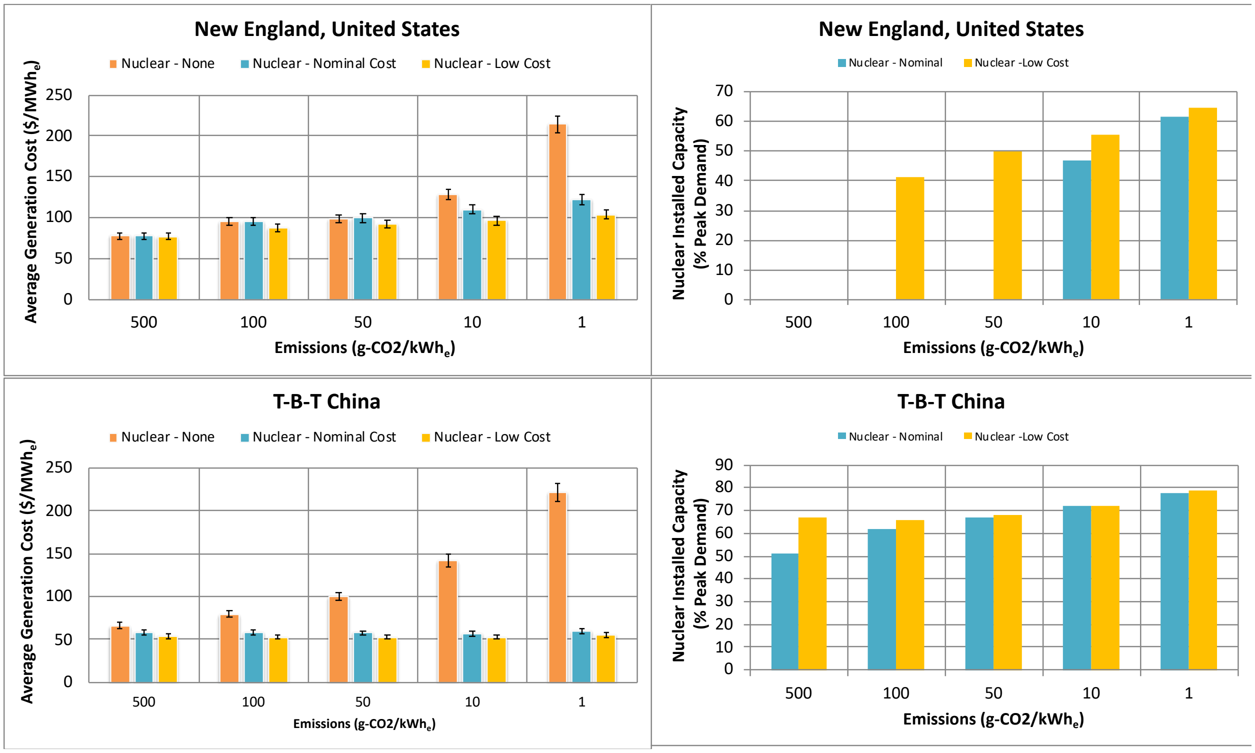


**Figure 3.** (Left) average system cost of electricity (in \$/MWh$_e$) and (right) nuclear installed capacity (% of peak demand) in the New England region of the United States and the Tianjin-Beijing-Tangshan (T-B-T) region of China for different carbon constraints (g$CO_2$/kWh$_e$) and three scenarios of various available technologies in 2050: (a) no nuclear allowed, (b) nuclear is allowed at nominal overnight capital cost (\$5,500 per kW$_e$ for New England and \$2,800 per kW$_e$ for T-B-T), and (c) nuclear is allowed with improved overnight capital cost (\$4,100 per kW$_e$ for New England and \$2,100 per kW$_e$ for T-B-T). Simulations were performed with an MIT system optimization tool called GenX. For a given power market the required inputs include hourly electricity demand, hourly weather patterns, economic costs (capital, operations, and fuel) for all power plants (nuclear, wind and solar with battery storage, fossil with and without carbon capture and storage), and their ramp-up rates. The GenX simulations were used to identify the electrical system generation mix that minimizes average system electricity costs in each of these markets. The cost escalation seen in the no-nuclear scenarios with aggressive carbon constraints is mostly due to the additional build-out and cost of energy storage, which becomes necessary in scenarios that rely exclusively on variable renewable energy technologies. The current world-average carbon intensity of the power sector is about 500 grams of $CO_2$ equivalent per kilowatt hour (g/kWh$_e$); according to climate change stabilization scenarios developed by the International Energy Agency in 2017, the power-sector carbon intensity targets to limit global average warming to 2°C range from 10 to 25 g/kWh$_e$ by 2050 and less than 2 g/kWh$_e$ by 2060.

In all the scenarios we analyzed, a certain flexibility in operations is required from the dispatchable power generators, because of the presence of variable renewables on the grid. Nuclear plants were traditionally designed for baseload operation, but, as has been recently demonstrated in Europe and the United States (Jenkins & al., 2018), nuclear plants can adapt to provide load-following generation and many advanced reactor concepts are being designed for that capability as well.

A key consideration is whether the deployment of low-carbon energy technologies like renewables or nuclear can be accomplished in the timeframe needed to substantially displace fossil fuels by 2050. Rapid deployment by that date is critical to achieve current international climate mitigation goals. In many countries, solar and wind have achieved notable levels of penetration in electricity generation markets over the last decade, and this trend is expected to continue. However, our analysis indicates that, historically, large-scale increases in low-carbon generation have occurred most rapidly in connection with additions of nuclear power (Figure 4).

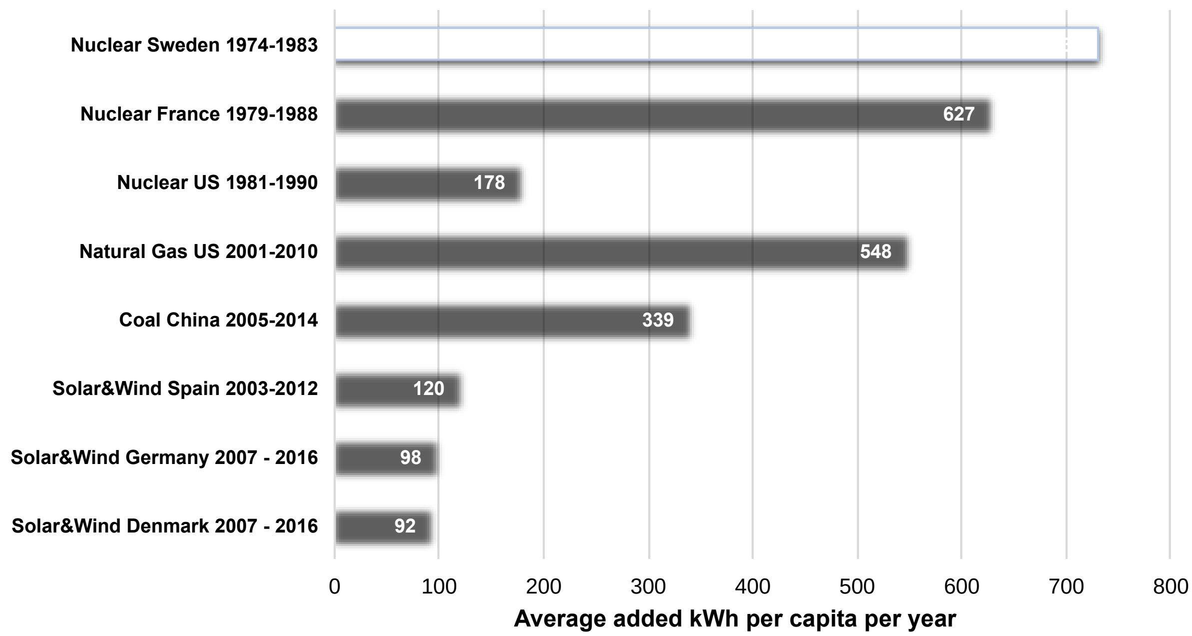


**Figure 4.** Electricity growth (kWh per year per capita) based on actual data for added power capacity in various countries. Assumes 90% capacity factor for dispatchable energy sources (nuclear, natural gas, coal) and the following capacity factors for wind/solar: Germany 19%/9%; Spain 25%/33%; Denmark 26%/7% (based on historical record for best 10-year period).

Nuclear energy does provide other benefits in addition to its low-carbon attribute. For example, it reduces air pollution associated with electricity production; it contributes to fuel diversification and grid stability, has low land requirements, and creates well-paid jobs. These benefits are important in certain contexts; for example, nuclear energy may be attractive in regions that do not have enough land or suitable weather patterns for large-scale deployment of renewables, or in countries that are seeking to reduce coal use to improve air quality, or that are concerned about the security and reliability of their energy supply. However, we believe that the primary, generally applicable attribute of nuclear energy that may justify its *future growth on a global scale* is its low-carbon nature. As such, special consideration should be given to preserving the existing nuclear power plant fleet in the U.S. and internationally, as it constitutes a bridge to the future in terms of emission avoidance (as recognized in recent legislation adopted by the U.S. states of New York (Larson, A., 2016), Illinois (Anderson, 2016), and New Jersey (Sethuraman, 2018)), and expertise essential for the operation of the future nuclear systems.

Despite the promise highlighted by our analyses, the prospects for the expansion of nuclear energy remain decidedly dim in many parts of the world. The fundamental problem is cost.

Other generation technologies have become cheaper in recent decades, while new nuclear plants have only become costlier. This disturbing trend undermines nuclear energy's potential contribution and increases the cost of achieving deep decarbonization. In the MIT study, we have examined what is needed to arrest and reverse that trend.

We have surveyed recent light water reactor (LWR) construction projects around the world and examined recent advances in crosscutting technologies that can be applied to nuclear plant construction for a wide range of advanced nuclear plant concepts and designs under development. To address cost concerns, we recommend:

(1) *An increased focus on using proven project/construction management practices to increase the probability of success in the execution and delivery of new nuclear power plants.*

The recent experience of nuclear construction projects in the United States and Europe has demonstrated repeated failures of construction management practices in terms of their ability to deliver products on time and within budget. Several corrective actions are urgently needed: (a) completing greater portions of the detailed design prior to construction; (b) using a proven supply chain and skilled workforce; (c) incorporating manufacturers and builders into design teams in the early stages of the design process to assure that plant systems, structures, and components are designed for efficient construction and manufacturing to relevant standards; (d) appointing a single primary contract manager with proven expertise in managing multiple independent subcontractors; (e) establishing a contracting structure that ensures all contractors have a vested interest in the success of the project; and (f) enabling a flexible regulatory environment that can accommodate small, unanticipated changes in design and construction in a timely fashion.

(2) *A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants.*

Opportunities exist to significantly reduce the capital cost and shorten the construction schedule for new nuclear power plants. First, the deployment of multiple, standardized units, especially at a single site, affords considerable learning from the construction of each unit. In the United States and Europe, where productivity at construction sites has been low, we also recommend expanded use of factory production to take advantage of the manufacturing sector's higher productivity when it comes to turning out complex systems, structures, and components. The use of an array of cross-cutting technologies, including modular construction in factories and shipyards, advanced concrete solutions (e.g., steel-plate composites, high-strength reinforcement steel, ultra-high performance concrete), seismic isolation technology, and advanced plant layouts (e.g., embedment, offshore siting), could have positive impacts on the cost and schedule of new nuclear power plant construction. For less complex systems, structures, and components, or at sites where construction productivity is high (as in Asia), conventional approaches may be the lowest-cost option.

We emphasize the broad applicability of these recommendations across all reactor concepts and designs. Cost-cutting opportunities are pertinent to evolutionary Generation-III LWRs, SMRs, and Generation-IV reactors. Without design standardization and innovations in construction approaches, we do not believe the inherent technological features of any of the advanced reactors will produce the level of cost reductions needed to make nuclear electricity competitive with other generation options.

In addition to its high cost, the growth of nuclear energy has been hindered by public concerns about the consequences of severe accidents (such as occurred at Fukushima, Japan in 2011) in traditional Generation-II nuclear power plant designs. These concerns have led some countries to renounce nuclear power entirely. To address safety concerns, we recommend:

(3) *A shift toward reactor designs that incorporate inherent and passive safety features.*

Core materials that have high chemical and physical stability, high heat capacity, negative reactivity feedbacks, and high retention of fission products, together with engineered safety systems that require limited or no emergency AC power and minimal external intervention, will likely make operations simpler and more tolerable to human errors. Such design evolution has already occurred in some Generation-III LWRs and is exhibited in new plants built in China, Russia, and the United States. Passive safety designs can reduce the probability that a severe accident occurs, while also mitigating the offsite consequences in the event an accident does occur. Such designs can also ease the licensing of new plants and accelerate their deployment in developed and developing countries. We judge that advanced reactors like LWR-based SMRs (e.g., NuScale) and mature Generation-IV reactor concepts (e.g., high-temperature gas reactors and sodium-cooled fast reactors) also possess such features and are now ready for commercial deployment. Further, our assessment of the U.S. and international regulatory environments suggests that the current regulatory system is flexible enough to accommodate licensing of these advanced reactor designs. Certain modifications to the current regulatory framework could improve the efficiency and efficacy of licensing reviews.

Lastly, key actions by policy makers are also needed to capture the benefits of nuclear energy:

(4) *Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.*

Investors in nuclear innovation must see the possibility of earning a profit based on selling their products at full value, which should include factors such as the value of reducing $CO_2$ emissions that are external to the market. Policies that foreclose a role for nuclear energy discourage investment in nuclear technology, may raise the cost of decarbonization and slow progress toward climate change mitigation goals. Germany's own experience with its Energiewende illustrates the difficulty. Despite a massive investment in renewables, greenhouse gas emissions from the electricity sector have declined less than 20% between 2007 and 2017 (German Environment Agency, 2017). Increased generation from renewables has to a significant degree been used to replace nuclear instead of reducing emissions. Consequently, the government has acknowledged that current measures are unlikely to achieve the overall 40% emissions reduction target by 2020 (German Environment Agency, 2018). A more effective approach in Germany and elsewhere would seek to incorporate $CO_2$ emissions costs into the price of electricity and thus allow for more equitable recognition of the value of all climate-friendly energy technologies, such as nuclear, hydro, wind, solar, and even fossil fuels with carbon capture.

Historically, time-to-market and development costs for new nuclear reactors have been too high, making them fundamentally unattractive to private investors, and leading some to advocate for direct government involvement in the development of these technologies (Secretary of Energy Advisory Board, 2016). Prototype Generation-IV systems are currently being explored by the governments of several countries, including China, which has deployed high-temperature gas-cooled reactors (HTGRs) (Zhang & al., 2016), Russia (Digges, 2016), and India (Patel, 2017), both of which have deployed sodium-cooled fast reactors (SFRs). For the U.S. and other market-oriented countries we recommend an important, albeit more limited, role for governments in the development and deployment of new nuclear technologies, as follows:

(5) *Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing*.

Such sites should be open to diverse reactor concepts chosen by the companies that are interested in testing prototypes. The government should provide appropriate supervision and support—including safety protocols, infrastructure, environmental approvals, and fuel-cycle services—and should also be directly involved with all testing.

(6) *Governments should establish funding programs around prototype testing and commercial deployment of advanced reactor designs using four levers: (a) funding to share regulatory licensing costs, (b) funding to share research and development costs, (c) funding for the achievement of specific technical milestones, and (d) funding for initial new design prototypes or first-of-a-kind reactors*.

The MIT study did not address the disposal of radioactive waste (or, more properly, spent nuclear fuel) or proliferation risks. While these issues are universally considered barriers to the expansion of nuclear energy use, the political dimensions of finding solutions to waste disposal and managing proliferation risks far outweigh the technical challenges. We have reviewed recent studies of the nuclear fuel cycle that focused on the management and disposal of spent fuel (Blue Ribbon Commission on America's Nuclear Future, 2011) (Kazimi, et al., 2011) (Wigeland & al., 2014) and have found their recommendations to be valid. Briefly, there exist robust technical solutions for spent fuel management, such as interim storage in dry casks and permanent disposal in geological repositories with excavated tunnels or deep boreholes—the greater difficulty, historically, has been siting such facilities. But the evidence suggests that these solutions can be implemented through a well-managed, consensus-based decision-making process, as has been demonstrated in Finland (Fountain, 2017) and Sweden (Plumer, 2012). Domestically, the U.S. government should follow these examples and swiftly move on the recommendations for spent fuel management that have been put before it.

The question of nuclear materials proliferation is more complex. Adopting certain fuel cycle facilities such as international fuel banks and centralized spent fuel repositories can make the civilian nuclear fuel cycle unattractive as a path to gaining nuclear weapons materials or capability. At the same time, there is a desire on the part of established nuclear countries to supply nuclear technologies to newcomer countries, both because it constitutes a business opportunity and as a means to gain considerable, decades-long geopolitical influence in key regions of the world. Currently Russia and, to a lesser extent, China are aggressively pursuing opportunities to supply nuclear energy technology to other countries. Some have argued that if the United States and Western Europe wish to pursue such opportunities and advance other geo-political objectives while simultaneously sustaining the non-proliferation and safety norms they has advocated around the world, they have a compelling interest in maintaining a robust domestic nuclear industry (Moniz, 2017) (Center for Strategic and International Studies, 2018) (Aumeier & Allen, 2008).

## Conclusions

Based on the findings that emerged from this study, we contend that, as of today and for decades to come, the main value of nuclear energy lies in its potential contribution to decarbonizing the power sector. Further, we conclude that cost is the main barrier to fully realizing this value. Without cost reductions, nuclear energy will not play a significant role. We find that that there are ways to reduce nuclear energy's cost, which the industry must pursue aggressively and expeditiously. Lastly, we recognize that government help, in the form of well-designed energy and environmental policies and appropriate assistance in the early stages of new nuclear system deployment, is needed to realize the full potential of nuclear.

## Acknowledgements

The study was conducted by a multidisciplinary team of over twenty faculty, students and consultants, led by the four authors of this paper. The study report can be downloaded at the MIT Energy initiative website (http://energy.mit.edu/). We gratefully acknowledge the support of our major sponsor The Alfred P. Sloan Foundation and important contributions from Shell, Électricité de France (EDF), The David and Lucile Packard Foundation, General Atomics, the Anthropocene Institute, MIT's International Policy Laboratory, Mr. Zach Pate, Mr. Neil Rasmussen, and Dr. James Del Favero. We also thank the Idaho National Laboratory, Dominion Engineering Inc., Blumont Engineering Solutions, Professor Giorgio Locatelli from the University of Leeds, the Breakthrough Institute, and Lucid Strategy for their generous in-kind contributions.

## References

115th U.S. Congress. (2017-2018). Nuclear Energy Innovation Capabilities Act / Advanced Nuclear Energy Technologies Act.

Anderson, J. (2016). *Illinois governor signs energy bill to keep nuclear plants open, boost renewables*. Retrieved from American Public Power Association: https://www.publicpower.org/periodical/article/illinois-governor-signs-energy-bill-keep-nuclear-plants-open-boost-renewables

ANL-INL-ORNL. (2016). *Advanced Demonstration and Test Reactor Options, INL/EXT-16-37867, Rev. 1.*

Aumeier, S., and Allen, T. (2008, Winter). How to Reinvigorate U.S. Commercial Nuclear Energy. *Issues in Science and Technology*.

BBC News. (2017). *Hinkley Point: EDF adds £1.5bn to nuclear plant cost*. Retrieved from BBC News: https://www.bbc.com/news/business-40479053

Blue Ribbon Commission on America's Nuclear Future. (2011). *Report to the Secretary of Energy*.

Brinton, S. (2015). *The Advanced Nuclear Industry*. Retrieved from Third Way: https://www.thirdway.org/report/the-advanced-nuclear-industry

Buongiorno, J. et al. (2018), *The Future of Nuclear Energy in a Carbon-Constrained World*. MIT.

Cardwell, D., & Soble, J. (2017). *Westinghouse Files for Bankruptcy, in Blow to Nuclear Power*. Retrieved from The New York Times: https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html

Center for Strategic and International Studies. (2018). *Assessing the 2018 Nuclear Posture Review*. Retrieved from https://www.csis.org/events/assessign-2018-nuclear-posture-review

Deutch, J., Moniz, E., Ansolabehere, S., Driscoll, M., Gray, P., Holdren, J., Todreas, N. (2003). *The Future of Nuclear Power.* MIT.

Digges, C. (2016, November). Russia's newest breeder reactor goes into commercial operation. *Bellona.org*.

Dotson, S. (2014). *Lessons Learned from Kewaunee's Closing*. Retrieved from Power Engineering: https://www.power-eng.com/articles/npi/print/volume-7/issue-3/nucleus/lessons-learned-from-kewaunee-s-closing.html

Downey, J. (2017). *Guarantee may not be enough to save troubled V.C. Summer nuclear project*. Retrieved from Charlotte Business Journal: https://www.bizjournals.com/charlotte/news/2017/07/27/toshiba-guaranty-may-not-be-enough-to-save-the.html

Fountain, H. (2017, June 9). On Nuclear Waste, Finland shows U.S. how it can be done. *The New York Times*.

Generation-IV International Forum. (2014). *Technology Roadmap Update for Generation-IV Nuclear Energy Systems.*

German Environment Agency. (2017). National Inventory Reports for the German Greenhouse Gas Inventory 1990 to 2016 (as of 01/2018) and initial forecast for 2017.

German Environment Agency. (2018). Press Release. August 2018.

Hals, T., and DiNapoli, J. (2018). *Westinghouse reaches deal to resolve bankruptcy*. Retrieved from Reuters: https://www.reuters.com/article/us-toshiba-accounting-westinghouse-bankr/exclusive-westinghouse-reaches-deal-to-resolve-bankruptcy-sources-idUSKBN1F62WG

Hansen, J., Emanuel, K., Caldeira, K., and Wigley, T. (2015). *Nuclear power paves the only viable path forward on climate change*. Retrieved from The Guardian:

https://www.theguardian.com/environment/2015/dec/03/nuclear-power-paves-the-only-viable-path-forward-on-climate-change

International Atomic Energy Agency. (2017). *The Database on Nuclear Power Reactors*. Retrieved from Power Reactor Information System: https://www.iaea.org/pris

International Energy Agency. (2017). Retrieved from https://www.iea.org

Jenkins, J., et al. (2018). The benefits of nuclear flexibility in power system operations with renewable energy. *Applied Energy*(222), 872-884.

Kazimi, M., Moniz, E., Forsberg, C., Ansolabehere, S., Deutch, J., Driscoll, M., Regalbuto, M. (2011). *The Future of the Nuclear Fuel Cycle*. MIT.

Larson, A. (2016). *N.Y. Approves Nuclear Subsidies and Mandates 50% Renewables by 2030*. Retrieved from Power: http://www.powermag.com/n-y-approves-nuclear-subsidies-and-mandates-50-renewables-by-2030

Larson, A. (2016). *Sweet Dreams Fort Calhoun Nuclear Plant*. Retrieved from Power: http://www.powermag.com/sweet-dreams-fort-calhoun-nuclear-plant

Moniz, E. (2017). *The U.S. Nuclear Energy Enterprise: A Key National Security Enabler*. Energy Futures Initiative.

Mufson, S. (2013). *San Onofre nuclear power plant to shut down*. Retrieved from The Washington Post: https://www.washingtonpost.com/business/economy/san-onofre-nuclear-power-plant-to-shut-down

Patel, S. (2017). *India Gears up to Expand Fast Breeder Reactor Fleet*. Retrieved from Power Magazine: http://www.powermag.com/india-gears-up-to-expand-fast-breeder-reactor-fleet

Penn, I. (2013). *Duke Energy announces closing of Crystal River nuclear power plant*. Retrieved from Tampa Bay Times: http://www.tampabay.com/news/business/energy/duke-energy-announces-closing-of-crystal-river-nuclear-power-plant/1273794

Plumer, B. (2012, January 28). What Sweden can teach us about nuclear waste. *The Washington Post*.

Plumer, B. (2017). *U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned*. Retrieved from The New York Times: https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html

Proctor, D. (2017). *Cost Overruns at Vogtle Expected to Soar*. Retrieved from Power: http://www.powermag.com/cost-overruns-at-vogtle-expected-to-soar

Reuters. (2018). *EDF says Flamanville weldings problems worse than expected*. Retrieved from Reuters: https://www.reuters.com/article/edf-flamanville/update-2-edf-says-flamanville-weldings-problems-worse-than-expected-idUSL8N1RN1E6

Rosendahl, J., and Forsell, T. (2017). *Areva's Finland reactor to start in 2019 after another delay*. Retrieved from Reuters: https://www.reuters.com/article/us-finland-nuclear-olkiluoto/arevas-finland-reactor-to-start-in-2019-after-another-delay-idUSKBN1CE1ND

Secretary of Energy Advisory Board. (2016). *Report on the Task Force on the Future of Nuclear Power*.

Sethuraman, R. N. (2018). *New Jersey Senate, Assembly passes nuclear subsidy bill*. Retrieved from Reuters: https://www.reuters.com/article/pseg-nuclear-new-jersey-subsidies/update-1-new-jersey-senate-assembly-passes-nuclear-subsidy-bill-idUSL1N1RP2EN

(2008). *The Economics of Nuclear Power.* Information Papers, World Nuclear Association.

U.S. Energy Information Agency. (2017). *International Energy Outlook.* Retrieved from https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf

United Nations Development Programme. (2017). *Human Development Index.* Retrieved from Human Development Reports: http://hdr.undp.org/en/content/human-development-index-hdi

United Nations Scientific Committee on the Effects of Atomic Radiation. (2017). *Developments since the 2013 UNSCEAR report on the levels and effects of radiation exposure due to the nuclear accident following the Great East-Japan Earthquake and Tsunami - A 2017 white paper to guide the Scientific Committee's future programme of work.* New York.

Wigeland, R., at al. (2014). *Nuclear Fuel Cycle Evaluation and Screening - Final Report, INL/EXT-14-31465, FCRD-FCO-2014-000106.*

Winters, J. W., Corletti, M. M., & Thompson, M. (2001). AP1000 construction and operating costs. *9th International Conference On Nuclear Engineering (ICONE-9).* Nice, France.

World Nuclear Association. (2017). *Nuclear Power in Belgium*. Retrieved from http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx

World Nuclear Association. (2017). *Nuclear Power in Germany*. Retrieved from http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx

World Nuclear Association. (2017). *Nuclear Power in South Korea*. Retrieved from http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx

World Nuclear Association. (2017). *Nuclear Power in Switzerland*. Retrieved from http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.aspx

World Nuclear Association. (2017). *Nuclear Power in Taiwan*. Retrieved from http://www.world-nuclear.org/information-library/country-profiles/others/nuclear-power-in-taiwan.aspx

Zhang, Z., et al. (2016, March). The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation. *Engineering, 2*(1), 112-118.