Columbia | SIPA
Center on Global Energy Policy

WHY THE UNITED STATES SHOULD REMAIN ENGAGED ON NUCLEAR POWER: CLIMATE CHANGE AND AIR POLLUTION

BY MATT BOWEN
JUNE 2020

Preface

Nuclear energy has shown much promise and faced considerable challenges since its origins in the mid-20th century. While the United States drove the early charge for safe nuclear power around the globe, its leadership has waned in recent decades. US reactors now under construction—following no orders for such plants in the United States for several decades—have gone well over planned budgets and schedules. And while the United States was once the leading international supplier of reactors, other countries have since stepped forward to fill that role.

Columbia University's Center on Global Energy Policy, as part of its wider work on nuclear energy, is examining the impact of potential American disengagement from nuclear power's development and where opportunities exist to step back in and shape its future. The program also will assess the US nuclear waste management program and efforts to collaborate with other countries on advanced reactor development, as well as options for improvement on both fronts.

This effort will begin with a two-part commentary on some of the benefits the United States might derive from increasing its engagement on nuclear power. The first in the series, this piece, explores the important role nuclear energy can play in lowering greenhouse gas emissions to avoid the worst potential outcomes of climate change. The second piece will examine the geopolitical and national security implications of the United States and its traditional allies effectively ceding the international nuclear energy marketplace to the Chinese and Russians.

The nuclear program's ultimate goal is to inform readers—policy makers, industry leaders, academics, and others—with objective, research-based analysis. It will strive in the months and years ahead to contribute constructively to a necessary dialogue on the future of nuclear power.

Dr. Matt Bowen
Research Scholar
Center on Global Energy Policy, Columbia University

Introduction

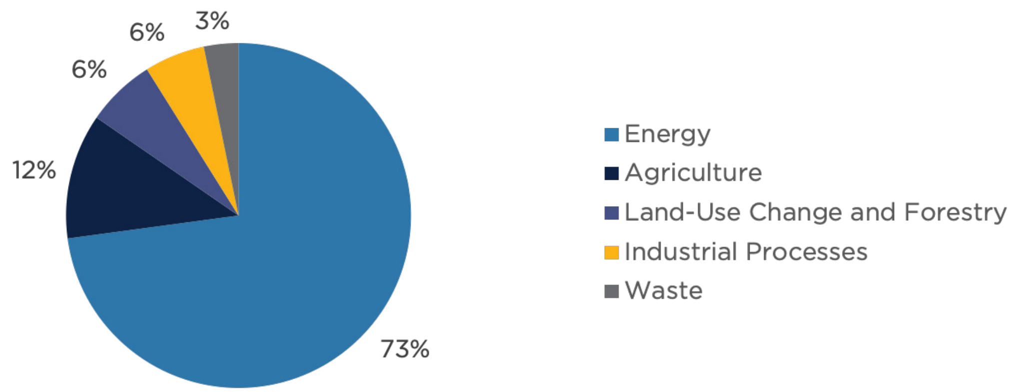
Nuclear power has the potential to help stem the advance of climate change and reduce air pollution by limiting the types of emissions that contribute to each. Despite its provision of reliable electricity and potential to play an even larger role in the fight against a warming planet and harmful pollution, nuclear power is facing headwinds in the United States, including mixed public acceptance, lack of progress on waste management, and cost overruns at new reactor builds. These challenges cloud nuclear energy's future in the United States at a time when much of the world is struggling to meet deep decarbonization goals and would benefit from American leadership.

Risks and Challenges of Climate Change

Despite increased attention to the risks posed by climate change, global greenhouse gas emissions have not yet begun to decline significantly and in fact have continued to grow in recent years. The failure of world governments to halt the rise of global warming emissions was noted in a 2019 United Nations publication that found "deeper and faster cuts are now required" and assessed that the world appears to be headed toward 3.9°C of warming by the end of the century.[1] A recent US government report warned of additional dangers, including that "thawing permafrost throughout the Arctic could begin releasing an estimated 300–600 million tons of net carbon per year to the atmosphere."[2] Continued greenhouse gas accumulation could increase the frequency and intensity of heat waves and storms and lead to other effects such as ocean acidification with associated changes to marine ecosystems. Abrupt changes with far more serious consequences cannot be discounted entirely either, as the last time carbon dioxide levels were as high as they are today was during the Pliocene Epoch about three to five million years ago. Back then, the world was 5.4°F to 7.2°F warmer, and the sea was 16 to 131 feet higher.[3] Studies have indicated that the Greenland ice sheet could conceivably melt in the next millennium in the absence of greenhouse gas emissions reductions, resulting in a 17- to 23-foot increase in sea level.[4]

The historic Paris Agreement in 2015 reflected a world consensus to try to keep the increase in global warming to less than 2°C to avoid such outcomes, though this appears ever more unlikely under current emissions trajectories. More troubling, with each passing year that emissions continue to grow, deeper and faster cuts will be required in the future to prevent the worst effects of climate change. As Figure 1 shows, around 73 percent of total global greenhouse gas emissions came from the energy sector in 2016, which argues for world efforts to focus on dramatically changing how nations use energy.

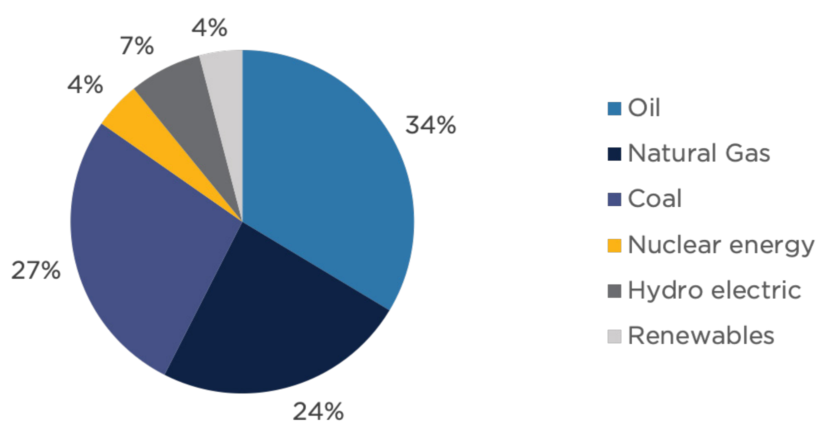
Figure 1: Global sources of greenhouse gas emissions in 2016 by sector



Source: Climate Watch, https://www.climatewatchdata.org/

As Figure 2 shows, the great majority (about 85 percent) of world energy still comes from the traditional use of fossil fuels. A 2019 International Energy Agency (IEA) analysis indicated that while energy efficiency, renewables, coal-to-gas switching, nuclear, and other measures helped to limit the amount of carbon emissions that resulted from the economic growth in 2018, expanded fossil fuel use still led to increased energy-related emissions.[5] As the head of the IEA, Fatih Birol, has noted regarding global electricity generation, "The share of low-carbon technologies has not changed over the last 20 years as the rising contribution of renewables has been offset by [the] declining role of nuclear."[6]

Figure 2: World energy consumption by fuel in 2018



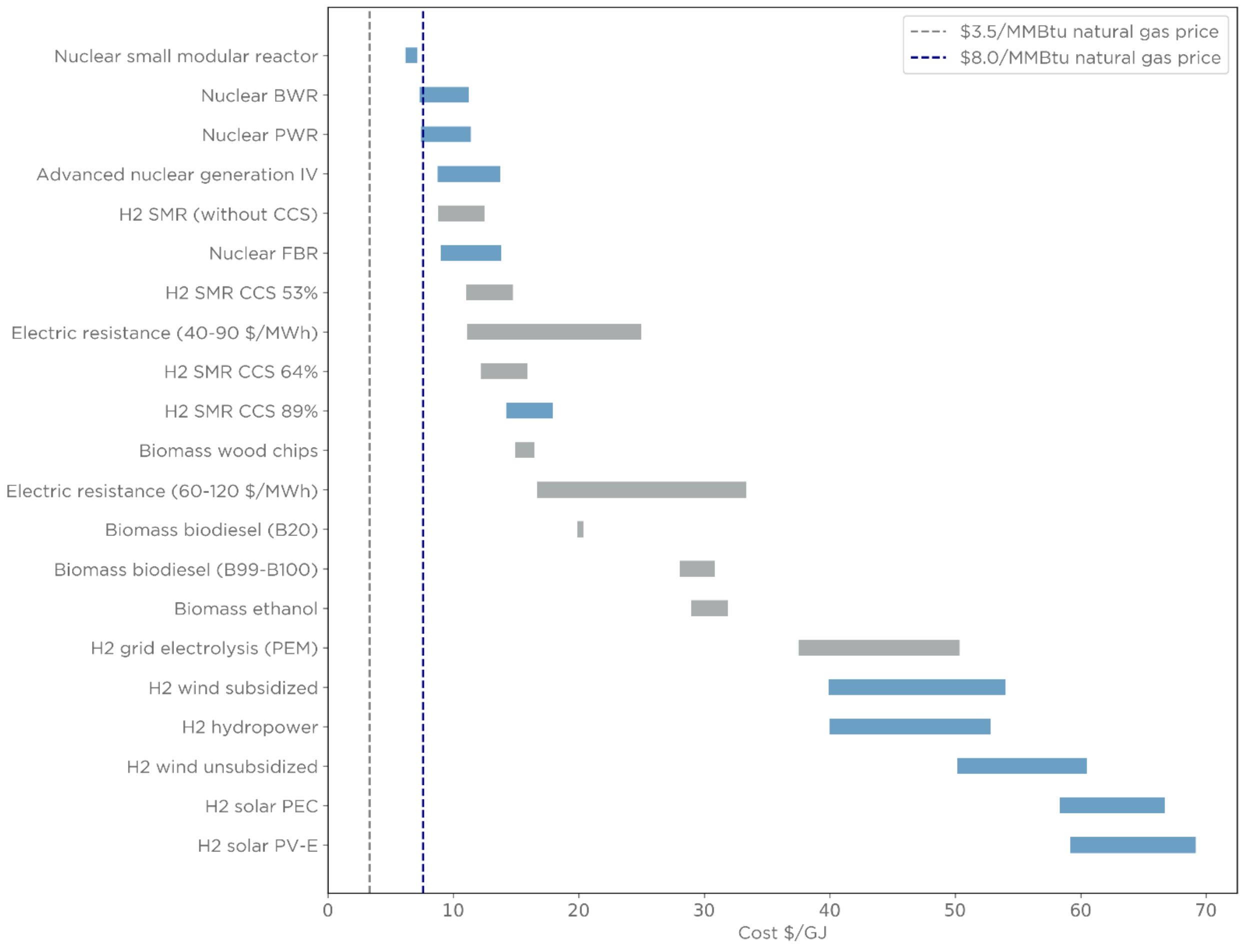
Source: BP Statistical Review of World Energy 2019

In the United States, some progress has at least been made towards reducing greenhouse gas emissions from the power sector, including a 28% decline between 2005 and 2017.[7] Limited demand growth, along with coal-to-gas switching and an increase in renewable energy usage, have combined to reduce greenhouse gas emissions associated with electricity generation. Policy initiatives at the state level have been some of the strongest measures taken to reduce emissions in recent years. As of November 2019, seven states and Puerto Rico and Washington, DC, had passed mandates for carbon-free energy by roughly midcentury.[8] Many US utilities have also pledged to decarbonize their electricity supply by roughly midcentury, including DTE Energy, Duke Energy, Idaho Power, Xcel Energy, and others.

Outside the power sector, at least part of the US transportation sector could be electrified (e.g., using electric cars and buses), which would allow a decarbonized electricity supply to aid in reducing emissions in that sector as well. A National Renewable Energy Laboratory report from 2018 estimated that electric vehicles could in part drive an increase in US electricity consumption in 2050 by as much as 38 percent compared with business as usual, adding to the challenge and importance of power sector decarbonization.[9]

For economy-wide decarbonization, greenhouse gas emissions from the industrial sector will also have to be addressed. A recent report from the Center on Global Energy Policy noted that the fossil fuel combustion used to produce heat for industrial activities accounts for 10 percent of global emissions—more than emissions from all the world's cars and planes added together.[10] The report noted the difficulties with available approaches (e.g., challenges with carbon capture and sequestration and low-carbon hydrogen production) and discussed the cost uncertainties for each option, as illustrated in Figure 3. It concluded that options to replace existing fossil fuels in those industrial activities (e.g., cement and steel production) were limited and more and better options were needed (i.e., an innovation agenda needed to be set and pursued).

Figure 3: Generic cost comparison of different heat options



Source: S. Julio Friedmann, Zhiyuan Fan, and Ke Tang, "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," Center on Global Energy Policy, October 2019.

Health Effects of Air Pollution from Fossil Fuel Combustion

Separate from climate concerns, an additional problem with the traditional use of fossil fuels is the air pollution they produce and the associated effects on human health. The IEA has estimated that 6.5 million deaths each year can be attributed to poor air quality.[11] This assessment ranked air pollution as the fourth-largest threat to human health, behind high blood pressure, dietary risks, and smoking. The most important man-made sources of air pollution—accounting for 85 percent of particulate matter and almost all sulfur oxide and nitrogen oxide emissions—come from energy production, including unregulated, poorly regulated, or inefficient fuel combustion.

The health costs due to air pollution, however, are not reflected in the price of energy that consumers in the United States see from traditional fossil fuel plants. For example, natural gas plants and coal plants emit sulfur dioxide, particulate matter, nitrogen oxides, mercury, and other pollutants, but they do not pay for any of the costs associated with these emissions. After years of decline, air pollution rose in the United States after 2016 and caused nearly 10,000 additional early deaths from 2016 to 2018.[12]

In 2010, the National Research Council published a study titled, "Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use," which estimated that the external cost of coal use in the United States attributable to conventional air pollution was $32 per megawatt-hour (MWh) in 2005, and even with better pollution reduction controls on coal plants in the future it would still be $17/MWh in 2030. (The same study estimated that with an assumed marginal damage value of $30/ton carbon dioxide equivalent, climate-related damages from coal-fired plants would translate to a price of $30/MWh.)

Natural gas plants have a lower air pollution influence than coal plants and a correspondingly lower associated external health cost. The National Research Council study referenced above estimated health costs of only $1.6/MWh for natural gas plants, with an expectation that this would fall to $1.1/MWh by 2030. (Given that natural gas plants emit substantial carbon emissions, the costs associated with climate-related damages was estimated to be much larger: around $15/MWh.)

Zero-emission technologies like solar, wind, geothermal, and nuclear energy are thus disadvantaged in competing with natural gas and coal in the electricity markets in the sense that the latter are allowed to emit air pollution and greenhouse gases without paying for the associated costs.

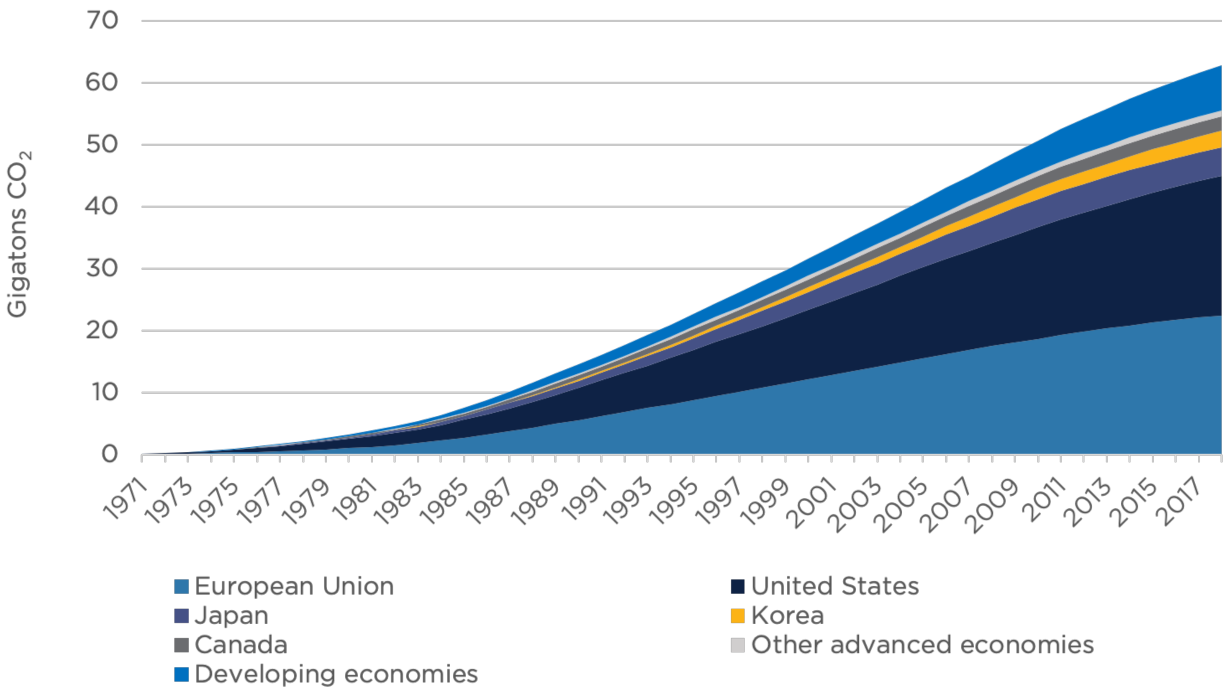
Nuclear Power's Potential Role

Nuclear power plants in particular would be more competitive in the US electricity markets if the external costs associated with the air pollution and greenhouse gas emissions from natural gas plants and coal plants were internalized in their respective market prices. Said differently, if the United States made a concerted effort to mitigate the risk posed by climate change and prevent damage to human health from air pollution, as long as nuclear power was not excluded from being part of the solution, such an initiative would aid nuclear energy's competitiveness.

In 2020, nuclear energy is used almost exclusively for power generation around the world. As the IEA has noted, nuclear power and hydropower "form the backbone of low-carbon electricity generation."[13] The two are the largest sources of zero-carbon dispatchable power in the world, though they have different geographical limitations for additional deployment. Hydropower plants, for example, require a source of water in a region with suitable topographical characteristics (i.e., some difference in elevation) for electricity generation, while at least current-generation large nuclear power plants require a source of water (e.g., rivers, lakes, or oceans) for cooling purposes.

Figure 4 shows an IEA chart illustrating how the past use of nuclear power has prevented 60 gigatons of carbon dioxide emissions in the last 50 years.

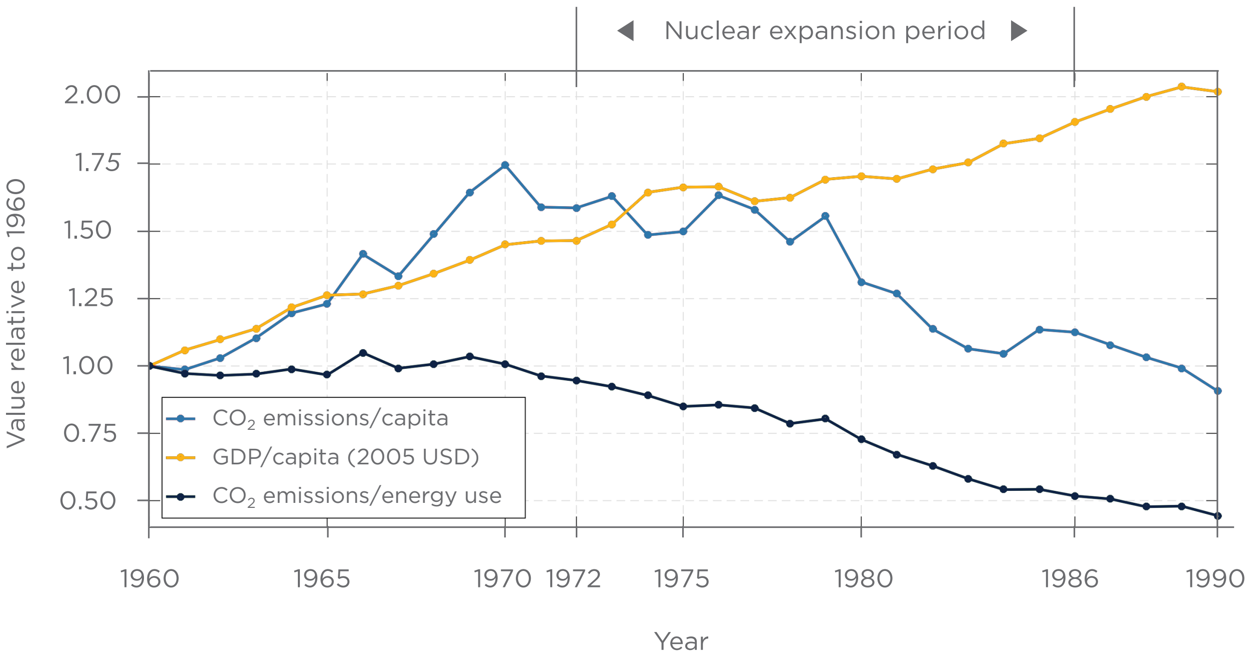
Figure 4: Cumulative CO_2 emissions avoided by global nuclear power in selected countries, 1971–2018



Source: IEA

Moreover, there are historical examples where countries have expanded their nuclear energy usage and in the process reduced their carbon emissions while simultaneously supporting a growing economy. Figure 5 shows the Swedish experience of building nuclear power plants from 1972 to 1986.[14] The Swedes were not trying to address climate change during this time period but were instead attempting to "reduce dependence on imported oil and protect four major Swedish rivers from hydropower installations." Today, Sweden's eight nuclear reactors currently supply around 40 percent of its electricity supply, and combined with other zero-carbon sources of energy, its power sector is nearly completely decarbonized. The country is also well into the process of licensing a geologic repository to dispose of its commercial spent nuclear fuel.[15]

Figure 5: Swedish experience with expanding nuclear energy usage



Note: During Sweden's nuclear power expansion period, the economy continued to grow while carbon emissions fell.
Source: S. A. Qvist and B. W. Brook, "Potential for Worldwide Displacement of Fossil-Fuel Electricity by Nuclear Energy in Three Decades Based on Extrapolation of Regional Deployment Data," PLOS ONE 10, no. 5 (2015): e0124074, https://doi.org/10.1371/journal.pone.0124074.

Rising concerns over climate change have prompted nations to consider nuclear power as one way to provide needed power without increasing their carbon footprint. The International Atomic Energy Agency estimated in 2017 that there were "28 countries interested in introducing nuclear power."[16] A 2016 World Nuclear Association (WNA) report analyzed several possible scenarios in the coming decades, including ones where the 440 operating nuclear reactors (in 2016) either grew to a maximum of 720 reactors or fell to a minimum of 362 units by 2035.[17] In the WNA reference case, worldwide operating reactors in 2035 reached 547, and the associated investment in new nuclear builds totaled around $1.5 trillion.

Broadly accepted analysis has consistently found that total system costs for deeply decarbonized systems are lower if they include a diverse set of energy sources (e.g., nuclear power and fossil plants equipped with carbon capture and sequestration) rather than rely exclusively on renewable energy.[18] For example, in 2019, the state of Washington passed the Clean Energy Transformation Act, directing utilities toward carbon-free electricity by 2045. Studies in the Pacific Northwest had previously found that deep decarbonization was possible in the area but that dispatchable zero-carbon generation was required to meet reliability standards (i.e., avoid blackouts) and keep energy supply affordable.[19]

As those studies—and others[20]—have pointed out, an underlying challenge with trying to build an electrical grid based solely on 100 percent renewable energy (an approach recommended by some papers[21]) is the variable nature of wind and solar energy. The challenge of overcoming periods of the year (days or weeks) with low to minimal solar and wind generation can be overcome in a technical sense, but doing so could lead to either an overbuild of renewable energy generation or a very large amount of storage capacity. These in turn could drive cost increases.[22] For example, one of the reports focusing on deep decarbonization in the Pacific Northwest assessed that "it would be extremely costly and impractical to replace all carbon-emitting firm generation capacity with solar, wind, and storage … Firm capacity is needed to meet the new paradigm of reliability planning under deep decarbonization, in which the electricity system must be designed to withstand prolonged periods of low renewable production once storage has depleted."[23]

A report published after the Washington state clean energy law passed concluded that small modular reactors (discussed below) could help to reduce the costs of achieving a 100 percent decarbonized electricity grid in the state of Washington by nearly $8 billion per year, in part by avoiding a large overbuild of renewables.[24] In this way, new nuclear power plants could help the United States to achieve decarbonization of the power sector at lower cost compared with an approach premised solely on renewable energy. The associated concern with a large cost increase in energy prices as part of decarbonization efforts is the negative economic effect from those higher costs as well as the potential to reduce public support for strong measures to address climate change.

Separate from electricity production, nuclear power has been studied as a potential source of zero-carbon heat to decarbonize sectors other than electricity generation. The Center on Global Energy Policy report on low-carbon heat discussed earlier in this commentary noted that the output temperatures in new nuclear reactors systems range "from 300 to about 850°C, enough to support ammonia production, methanol synthesis, [steam methane reforming] for hydrogen production, and supercritical steam for turbines and petrochemical reactions." In other words, nuclear energy could also be used as a heat source to produce fuels such as hydrogen, which could then be used to replace the fossil fuels burned for heat in industrial activities. Burning hydrogen could produce the substantially higher temperature (e.g., 1,500°C or 2,000°C) heat needed for some industrial activities such as cement and steel production.

In the United States, a group of private companies is seeking to commercialize a wide variety of different advanced reactor concepts. Their business strategies are in part premised on the notion that the United States and other nations will value the zero-carbon, dispatchable nature of their designs. Table 1 shows just a few US advanced reactor companies pursuing commercialization, to give a sense of the different technologies, temperatures, and power outputs being investigated.[25] Several of these companies plan to assemble larger plants from multiple smaller reactor modules (hence, "small modular reactor"). Multimodule plants would also enable greater flexibility to supply process heat from some modules and electricity supply from others at the same plant.[26] Small modular reactor developers have explored the use of nuclear energy for desalination, hydrogen production, oil recovery and refining operations, and balancing the output of variable renewable energy generation.[27]

Table 1: Selected advanced reactor coolants, power outputs, and nominal output temperatures

Company	Coolant	Coolant temperature	Module electrical output
NuScale Power	Water	300°C	60 MWe
TerraPower	Liquid sodium	500°C	300 MWe+
TerraPower	Molten chloride salt	650°C	300 MWe+
X-energy	Helium	565°C	75 MWe
Kairos Power	Molten fluoride salt	585°C	140 MWe

Source: NuScale Power, TerraPower, X-energy, and Kairos Power

In addition to climate benefits, new advanced reactors—particularly if they displaced coal-fired generation—would have air pollution benefits in the form of reduced nitrogen oxides, sulfur dioxide, particulate matter, mercury, and other pollutants. The retirement of existing nuclear reactors has been estimated in some studies to lead to substantial increases of air pollution with damage to nearby populations' health. For example, a Respiratory Health Association and Clean Air Task Force analysis in 2019 found that the potential retirement of four nuclear power plants in Illinois would, over a 10-year period, lead to the following:[28]

- Between 1,200 and almost 2,700 premature deaths
- Over 30,000 additional asthma attacks and other respiratory symptoms
- Almost 140,000 work loss days
- $10 to $24 billion in monetized damages

Conversely, the construction of new nuclear plants to displace existing coal generation would reduce current air pollution levels and prevent these types of associated effects on people's health and the economy.

Challenges Facing Nuclear Energy

Despite the urgency of addressing rising greenhouse gas accumulations and the health implications of polluted air and a warming planet, nuclear power is facing substantial headwinds in the United States. Though studies have shown that nuclear power is among the safest sources of energy,[29] public support in the United States for its usage is decidedly mixed.[30] The opposition to nuclear energy is in part based on safety concerns due to high-profile nuclear accidents at the Three Mile Island plant in the United States, the Chernobyl plant in Ukraine, and, most recently, the Fukushima Daiichi plant in Japan.

Contributing to reduced public acceptance for nuclear power, the US federal program to manage commercial spent nuclear fuel (SNF) has failed to produce a disposal option. The US

Department of Energy is responsible for producing a disposal site, though as of 2020, there is no licensed facility that can dispose of commercial SNF. The site selected by Congress in 1987, Yucca Mountain, is opposed by the governor and congressional delegation of Nevada as well as a majority of Nevadans. There have been no congressional appropriations for the project since 2010, and commercial SNF from reactors remains at power plant sites—even ones that have ceased operations—waiting to be shipped to either a location for consolidated interim storage or a geologic repository site for disposal. Multiple states have passed laws prohibiting new nuclear builds until and unless there is progress on addressing nuclear waste management.[31]

In addition, the Westinghouse AP1000 reactor projects in Georgia and South Carolina have gone over budget by billions of dollars and fallen years behind schedule, with the reactors in South Carolina canceled after billions of dollars in expenditures. While the reactors in Georgia are expected to begin operation in 2021 and 2022, they are many years late and billions of dollars over budget. They will be the first new reactors ordered since the early 1970s to enter into operation, but the dismal cost construction experience has cast a shadow over the possibility of future AP1000 builds. Further challenging new AP1000 builds or any other type of new reactor construction is the low price of natural gas in the United States, which has led to operating losses and economic pressures on existing nuclear power plants, particularly in deregulated states.

World trend lines regarding nuclear power vary by country. Following the Fukushima accident in 2011, Germany announced its intention to exit nuclear power entirely, and nuclear generation in that country has declined since then and is expected to disappear by 2022. Additional countries have also considered phasing out nuclear reactors. Electricity generation from nuclear power in another group of nations, such as the United States, Canada, and Mexico, has been relatively flat over the past decade with an unclear future. Meanwhile, Russia, China, and other countries have continued to grow their nuclear power programs.

Congressional Action

There are other reasons for the United States to remain engaged on nuclear beyond what is described in this commentary—for example, the benefits of having nuclear fuel at power plant sites that is sufficient for up to 18 to 24 months of continuous electricity production, the stability of nuclear power generation costs, or the diversification benefits of adding uranium to a portfolio of energy sources (e.g., as a hedge against future swings in natural gas prices).[32] The compact size of nuclear power plants can also reduce the amount of land that has to be developed as part of a decarbonized energy system, protecting more natural habitats.[33]

These rationales and more have fed into a recent bipartisan push in Congress toward the development of safer advanced reactors, with individual members of Congress placing differing levels of importance on the various reasons. In the 115th Congress (2017–2018), two bills passed into law with bipartisan support: the Nuclear Energy Innovation and Modernization Act and the Nuclear Energy Innovation Capabilities Act. More recently, the Nuclear Energy Leadership Act of 2019 was introduced in both chambers by a bipartisan group of members of Congress.[34] The bill would, among other directives, require the US Department of Energy to demonstrate several advanced reactor concepts over roughly the next decade.

Similarly, the Nuclear Waste Administration Act of 2019 was introduced by a bipartisan group of senators with the aim of putting the US commercial SNF management program on a better path. Specifically, the legislation would create a new organization whose sole focus would be nuclear waste management, including a consent-based approach to developing consolidated interim storage facilities and deep geologic repositories to safely isolate commercial SNF from the biosphere. Current US law and the approach taken to date have not produced a working site, and this new structure would be more in line with how other countries, such as Canada, have approached the development of geologic repositories for nuclear waste. Canada, Finland, and Sweden in particular have achieved substantial advances in developing geologic repositories for their commercial SNF in recent decades, and the United States stands to benefit from their progress.[35]

Conclusion

Given the challenges facing nuclear energy in the United States, its future is uncertain, despite the resource's zero-carbon emissions so eagerly sought by states and nations with climate commitments and pollution reduction goals. Building first-of-a-kind and subsequent advanced reactors on time and on budget will be central to nuclear power's future, and the United States can look to successful programs, such as that of South Korea, for lessons on project management for reactor construction.[36] Though headwinds abound, a concerted effort to bolster nuclear energy's prospects will help the United States and the world address energy and environmental challenges in dire need of actionable solutions.

Notes

1. *Emissions Gap Report 2019*, UN Environment Programme.
2. "Arctic Report Card: Update for 2019," NOAA, accessed May 22, 2020, https://www.arctic.noaa.gov/Report-Card/Report-Card-2019.
3. "Graphic: Carbon dioxide hits new high," NASA Climate Change, accessed May 22, 2020, https://climate.nasa.gov/climate_resources/7/graphic-carbon-dioxide-hits-new-high/.
4. Jessica Merzdorf, "Study Predicts More Long-Term Sea Level Rise from Greenland Ice," NASA, accessed May 22, 2020, https://www.nasa.gov/feature/goddard/2019/study-predicts-more-long-term-sea-level-rise-from-greenland-ice.
5. Global Energy & CO_2 Status Report 2019," IEA, accessed May 22, 2020, https://www.iea.org/reports/global-energy-and-co2-status-report-2019/emissions#abstract.
6. Fatih Birol, "A Shared Vision for Electrification," (opening keynote address, Electrification Europe 2019 International Summit, October 16, 2019), https://www.electrificationeurope.com/agenda.
7. "Carbon Dioxide Emissions from the U.S. Power Sector Have Declined 28% Since 2005," Energy Information Administration, October 29, 2018, https://www.eia.gov/todayinenergy/

detail.php?id=37392.

8. Third Way has produced a tracker for state clean energy actions: https://www.thirdway.org/graphic/clean-energy-targets-are-trending.

9. Trieu Mai et al., *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*, National Renewable Energy Laboratory, 2018, NREL/TP-6A20-71500, https://www.nrel.gov/docs/fy18osti/71500.pdf.

10. S. Julio Friedmann, Zhiyuan Fan, and Ke Tang, "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," Center on Global Energy Policy, October 2019, https://energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today.

11. "Energy and Air Pollution," World Energy Outlook Special Report, International Energy Agency, 2016.

12. Melissa C. Lott, "It's Not Just About Climate Change, It's About Our Health—and the Energy Sector Is Key," January 16, 2020. https://energypolicy.columbia.edu/research/op-ed/it-s-not-just-about-climate-change-it-s-about-our-health-and-energy-sector-key.

13. International Energy Agency, "Nuclear Power in a Clean Energy System," May 2019, https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system.

14. S. A. Qvist and B. W. Brook, "Potential for Worldwide Displacement of Fossil-Fuel Electricity by Nuclear Energy in Three Decades Based on Extrapolation of Regional Deployment Data," PLOS ONE 10, no. 5 (2015): e0124074, https://doi.org/10.1371/journal.pone.0124074.

15. "Nuclear Power in Sweden," World Nuclear Association, accessed May 22, 2020, https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/sweden.aspx.

16. "International Status and Prospects for Nuclear Power 2017," International Atomic Energy Agency.

17. Future Nuclear Supply Chain Worth Billions, Report Finds," World Nuclear News, September 14, 2016, https://www.world-nuclear-news.org/NN-Future-nuclear-supply-chain-worth-billions-report-finds-1509167.html.

18. For a review of several analyses, see the testimony of Karl Hausker, Senior Fellow, US Climate Program, World Resources Institute to the US House of Representatives, Energy and Commerce Committee, Subcommittee on Environment and Climate Change. Hearing on "Building America's Clean Future: Pathways to Decarbonize the Economy," July 24, 2019.

19. The collected studies can be found at https://www.publicgeneratingpool.com/e3-carbon-study/.

20. Christopher Clack et al., "Evaluation of a Proposal for Reliable Low-Cost Grid Power with 100% Wind, Water, and Solar," Proceedings of the National Academy of Sciences of the

United States of America, 114 (2017), 10.1073/pnas.1610381114.

21. M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. A. Frew, "Low-Cost Solution to the Grid Reliability Problem with 100% Penetration of Intermittent Wind, Water, and Solar for All Purposes," Proceedings of the National Academy of Sciences of the United States of America, 112 (2015): 15,060–15,065.

22. Nestor Sepulveda, Jesse Jenkins, Fernando Sisternes, and Richard Lester, "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation," Joule 2 (2018), 10.1016/j.joule.2018.08.006.

23. "Resource Adequacy in the Pacific Northwest," Energy and Environmental Economics, March 2019, http://www.publicgeneratingpool.com/e3-carbon-study/.

24. "Pacific Northwest Zero-Emitting Resources Study," Executive Summary, January 29, 2020, https://www.energy-northwest.com/Documents/E3%20Study%20Executive%20Summary%20final.pdf.

25. A more complete list of advanced reactor companies can be found at https://www.thirdway.org/graphic/2019-advanced-nuclear-map.

26. Ingersoll et al., "Extending Nuclear Energy to Non-Electrical Applications," Proceedings of the 19th Pacific Basin Nuclear Conference, August 24–28, 2014.

27. Ingersoll et al., "Can Nuclear Power and Renewables be Friends?" Proceedings of ICAPP 2015, May 3–6, 2015.

28. "Potential Human Health Impacts Associated with Retirement of Nuclear Power Plants in Illinois," Respiratory Health Association and Clean Air Task Force, 2019, https://www.catf.us/wp-content/uploads/2019/10/IL-Study.pdf.

29. P. A. Kharecha and J. E. Hansen, "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power, Environ. Sci. Technol. 47 (2013): 4,889–4,895, doi:10.1021/es3051197; Phil Mckenna, "Fossil Fuels Are Far Deadlier Than Nuclear Power," New Scientist, March 23, 2011, https://www.newscientist.com/article/mg20928053-600-fossil-fuels-are-far-deadlier-than-nuclear-power/; Hannah Ritchie, "What Are the Safest Sources of Energy?" February 10, 2020, https://ourworldindata.org/safest-sources-of-energy.

30. R. J. Reinhart, "40 Years after Three Mile Island, Americans Split on Nuclear Power," Gallup, March 27, 2019, https://news.gallup.com/poll/248048/years-three-mile-island-americans-split-nuclear-power.aspx.

31. See, for example, the list maintained by the National Conference on State Legislatures: https://www.ncsl.org/research/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility.aspx.

32. See pages 13–14 of the 2017 Nuclear Innovation Alliance report, "Leading on SMRs."

33. Heather Tallis et al., "An Attainable Global Vision for Conservation and Human Well-Being,"

Frontiers in Ecology and the Environment (2018), 10.1002/fee.1965.

34. S.903 was first introduced in the Senate, where the current (as of April 28, 2020) Republican cosponsors are Senators Murkowski, Alexander, Risch, Crapo, Capito, Sullivan, Graham, Portman, Gardner, Cramer, Braun, McSally, Tillis, and Blackburn. Democratic cosponsors are Senators Booker, Manchin, Whitehouse, Coons, Duckworth, Bennet, Jones, Cardin, and Warner.

35. "Reset of America's Nuclear Waste Management: Strategy and Policy," Stanford University and George Washington University, October 15, 2018.

36. "The Future of Nuclear Energy in a Carbon Constrained World," MIT (2018): 244—for example: "The standard Korean 1-gigawatt power plant design has been consistently built on budget and within a reasonable schedule (five to six years), and the existing fleet of Korean reactors has had good operational performance."

Acknowledgments

The views in this commentary represent those of the author.

This work was made possible by support from the Center on Global Energy Policy. More information is available at https://energypolicy.columbia.edu/about/partners.

About the Author

Matt Bowen is a research scholar at the Center on Global Energy Policy (CGEP), focused on nuclear energy, waste, and nonproliferation. Before joining CGEP, he held positions at Clean Air Task Force and the Nuclear Innovation Alliance. Bowen spent over four years at the US Department of Energy (DOE) as a senior advisor in the Office of Nonproliferation and Arms Control from 2011 to 2015. He left DOE in January 2017 as an associate deputy assistant secretary in the Office of Nuclear Energy. Bowen has a PhD in theoretical particle physics from the University of Washington, Seattle and a BS in physics from Brown University.

ABOUT THE CENTER ON GLOBAL ENERGY POLICY

The Center on Global Energy Policy provides independent, balanced, data-driven analysis to help policymakers navigate the complex world of energy. We approach energy as an economic, security, and environmental concern. And we draw on the resources of a world-class institution, faculty with real-world experience, and a location in the world's finance and media capital.

Visit us at www.energypolicy.columbia.edu

@ColumbiaUenergy

ABOUT THE SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS

SIPA's mission is to empower people to serve the global public interest. Our goal is to foster economic growth, sustainable development, social progress, and democratic governance by educating public policy professionals, producing policy-related research, and conveying the results to the world. Based in New York City, with a student body that is 50 percent international and educational partners in cities around the world, SIPA is the most global of public policy schools.

For more information, please visit www.sipa.columbia.edu