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A Roadmap for U.S. Nuclear Energy Innovation

A variety of timely forces are inspiring a renewed push for nuclear energy. Here is a proposed roadmap for innovation over the next few decades.

The future role of nuclear energy is attracting new attention. Several recent climate policy assessments have concluded that meeting the world's growing appetite for energy while achieving deep reductions in global greenhouse gas emissions will be impossible without rapid nuclear energy growth, along with massive increases in the deployment of solar, wind, and other low-carbon energy technologies. But if nuclear energy is indeed to play such a role, the United States seems unlikely to be much of a factor at this point.

Once the undisputed global leader, the U.S. nuclear energy industry is now well on its way to second-tier status. The new leaders include China and, notably, Russia, whose aggressive nuclear exporters are one of the few bright spots in that nation's troubled economy. Meanwhile, the U.S. fleet of 100 nuclear power reactors, still the world's largest and the source of almost two-thirds of the nation's low-carbon electricity, is slowly shrinking. Five operating reactors have recently closed, and several more will be retired in the next few years. As the rest of the nuclear fleet ages, many more reactors seem likely to be shuttered over the next couple of decades.

The outlook for new reactors is also grim. Four reactors are under construction in the Southeast, and a fifth is being completed after a long delay. There are no firm plans to build more. High construction costs, an uncertain demand outlook, and the availability of inexpensive natural gas are the main deterrents to new nuclear investment, and today the nuclear part of the government's climate policy amounts to little more than a hope that additional premature shutdowns can be avoided and that some reactors will be able to stay open for longer than planned. Without a more serious federal policy this may be a vain hope, and it is certainly a strategic weakness. Losing the existing nuclear fleet would wipe out much of reduction in carbon dioxide (CO_2) emissions promised by the Obama administration's Clean Power Plan.

And yet, mostly below the radar, a new wave of nuclear energy innovation is building. More than 30 advanced reactor development projects have been launched since the 1990s. Most of this activity has been funded privately. According to one estimate, more than $1.3 billion in private investment has already been committed. But public funding and risk-sharing will also be needed if new nuclear technologies are to be brought to market successfully. Today, though, the federal government has no strategy for nuclear innovation, and there is resistance to developing one on both sides of the political aisle. Some influential Democratic lawmakers believe that a combination of renewables and increased energy efficiency will be sufficient to achieve global emission reduction goals. Some also fear that the safety and security risks of an increased nuclear commitment would more than offset the climate benefits it would bring. Among Republicans, many assign far greater importance to reducing government spending than to reducing greenhouse gas emissions.

Against this picture, I envision a new roadmap for nuclear innovation in the United States. This roadmap identifies three successive waves of advances: the first breaking during the next decade or so and supporting longer operating lifetimes for at least some of the existing nuclear fleet; the second arriving during the critical period between 2030 and 2040, when rapid scale-up of nuclear energy will be needed to achieve deep emissions reductions just as much of the current reactor fleet is being phased out; and the third wave breaking during the post-2050 period, when further deep cuts in CO_2 emissions will be needed even if the world succeeds in meeting the ambitious mid-century mitigation targets to which many countries have signed up.

New work on all three waves will need to begin immediately. The roadmap also calls for significant reform of the Nuclear Regulatory Commission (NRC), a new and unfamiliar role for the national laboratories, and a supporting, rather than directive, role for federal nuclear managers in the Department of Energy, including support for international collaborations in which U.S. innovators are engaged.

This nuclear agenda is ambitious, but attainable. It draws on the deep strengths of the U.S. economy in entrepreneurial risk-taking, as well as on a series of remarkable advances in other scientific fields that can now be applied to the traditionally insular and conservative nuclear industry. It also draws on the still-formidable capabilities of the nation's nuclear research and security complex. But implementing this innovation agenda will require a new political coalition capable of neutralizing the longstanding opposition of people for whom the biggest dragons to be slain are nuclear energy or the federal government itself. A failure to act will undermine U.S. climate goals. It will also compromise important national security objectives. And it will further disconnect the nation's industry from a global nuclear marketplace that is likely to be worth many hundreds of billions of dollars in the coming decades.

Uncertain outlook for innovation

The most visible of the new wave of nuclear innovators is TerraPower, an 8-year-old company co-founded by Bill Gates. Its main development effort focuses on an old idea (the so-called "breed-and-burn" reactor design concept), combined with the latest developments in instrumentation and control, materials science, nanotechnology, and computation and simulation—capabilities that were unimaginable 50 years ago when breed-and-burn was first considered. A similar combination of old ideas and forefront science and engineering also characterizes several new ventures in the field of molten-salt-cooled reactors (where TerraPower is also active.)

The industry that supplies and operates light-water reactors (LWRs), the dominant nuclear reactor technology around the world, has been slower to adopt new technology. But even here, there are important innovations. NuScale, an early-stage U.S. company, has developed a radically different (and much smaller) LWR configuration that promises major upgrades in safety relative to today's LWRs. Fluor, a major engineering and construction company with decades of experience in nuclear power, is the majority investor in NuScale. Other developers are pursuing different systems, using different kinds of nuclear fuel and coolant.

The new nuclear agenda has captured the imagination of young researchers at the nation's universities. NuScale was spun out of Oregon State University. And at my own department of nuclear science and engineering at the Massachusetts Institute of Technology (MIT), one group of faculty and students is developing a new concept for a floating nuclear plant, a second has co-invented and is advancing a new kind of molten-salt-cooled reactor, a third has proposed a new fusion reactor design that it believes has promise of early commercialization, and two new reactor development companies have recently been formed by graduate students.

It is premature at this stage to attempt to identify a winner among all these innovations, or even whether there will be one. What their developers have in common is the conviction that nuclear energy has a key role to play worldwide, but to realize its full potential, a technology that is already much safer than it was when the first LWRs were built a half-century ago will need to be made safer still. New reactors will also need to be less expensive, easier and faster to build, less vulnerable to security threats, better suited to the needs of developing countries, and more compatible with the rapidly changing characteristics of electric power grids, which are being transformed by the introduction of advanced grid technologies as well as growing amounts of intermittent wind and solar generating capacity.

The federal government, whose role in the nuclear energy field has long been atypically *dirigiste*, or centrally controlling, has been taken by surprise by

David Buckland, *Burning Ice*, 2008.

David Buckland is the founding director of Cape Farewell, which has worked since 2001 to unite artists, scientists, and communicators around the world to instigate a cultural response to climate change. A designer, artist, and filmmaker, his *Burning Ice* photograph is from a series where he projected text onto glaciers at dawn when, for a short window of time due to light conditions, both the message and the ice were visible. Cape Farewell is an organizer of ArtCop21.

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these developments and is scrambling to catch up. In recent years, its support for nuclear innovation has zigzagged from one priority to another. A program to develop improvements to large LWRs was the main priority for a while, but has since been dropped. Another program to build a prototype high temperature gas-cooled reactor jointly with industry failed to attract sufficient industry interest and has also ended. The government then launched a program to assist in the commercialization of small, modular LWRs, but one of the two horses it backed has since dropped out of the race. Support for the other (NuScale) continues. Most recently, the government has announced a new competition to provide a small amount of funding for earlier-stage research and development (R&D) for two advanced reactor concepts, not limited either to small reactors or to light-water technology.

The history of unsuccessful government efforts to commercialize new nuclear power reactor technologies stretches back much further. The best-known example involved the liquid-metal-cooled fast breeder reactor, a costly effort that was abandoned in the 1970s. In fact, the only successful counterexample occurred at the outset of the nuclear energy era, when a government-funded civilian reactor demonstration program enabled the emergence of the LWR technology that subsequently came to dominate the industry worldwide. That outcome was, in turn, enabled by the earlier development of pressurized water reactor technology for naval propulsion. Critical to those developments was the extraordinary leadership of Admiral Hyman Rickover, who headed the naval reactors program and was also the principal driving force for transferring this technology into the civilian power sector. The uniqueness of that early success and the subsequent string of failures suggest that new models of government involvement will be needed if advanced nuclear power technologies are to be commercialized successfully in the future.

An even bigger deterrent to nuclear innovation today is the licensing and regulatory process administered by the NRC. The current body of technical requirements and procedures was developed with today's LWR technologies in mind, and it is generally considered to work reasonably well for them. But those regulations are not always well-suited to advanced reactor concepts, which in some cases rely on fundamentally different approaches to achieving acceptable levels of safety. Also, licensing procedures that have evolved over the years to accommodate incremental changes in LWR designs are less suitable for radically different reactor technologies. Would-be developers of such technologies face the prospect of having to spend a billion dollars or more on an open-ended, all-or-nothing licensing process without any certainty of outcomes or even clear milestones along the way.

NRC officials have met the calls for regulatory reform with mixed signals. Some have dismissed the need for reform. Others have acknowledged that different approaches may be needed for new technologies, but have also suggested that they would need to see commercial commitments from prospective customers before embarking on a new regulatory development effort. This is an unrealistic demand, since no new customer would be prepared to make a commitment of that kind in the face of such large regulatory risks. But the NRC also points out that roughly 90 percent of its budget is funded by licensing fees paid by the utility operators of current nuclear power plants. Most of these operators are paying no attention to advanced nuclear technologies and have no interest in seeing their fees applied to a new regulatory development activity.

These obstacles have caused several U.S. nuclear innovators to look to other countries, including Canada and South Korea, in search of a more encouraging regulatory environment. TerraPower declared that because of the regulatory problem it would not build its first prototype reactor in the United States. In September 2015, the company signed an agreement to jointly develop and commercialize its breed-and-burn technology with China National Nuclear Corporation, making it almost certain that the first reactor of this type will be built in China.

The highest priority of nuclear innovation policy should be to promote the availability of an advanced nuclear power system 15 to 20 years from now.

China is also setting the pace in other fields of advanced nuclear technology. Indeed, the U.S. government itself, unsure of its domestic agenda, has been helping to boost China's nuclear innovation efforts. It has encouraged the federal Oak Ridge National Laboratory, which pioneered the development of molten-salt-cooled reactors in the 1950s and 1960s, to share the residual knowledge and technology from that program with China. The Chinese have identified molten-salt reactors as a high development priority and are planning to start up a small prototype device within two years.

Thus the outlook for nuclear innovation in the United States today is uncertain. The upsurge of interest in advanced nuclear technologies is remarkable, and the possibility that these technologies could help solve the world's climate challenges has attracted the attention of a small, but growing, group of U.S. entrepreneurs and investors. But the combination of an uncertain regulatory environment and anemic federal policies toward nuclear innovation could help drive leadership of the new generation of technologies away from the United States—a dispiriting coda to the ongoing loss of U.S. leadership in today's LWR industry.

Why innovation matters

Would this matter? Some influential energy and environmental experts both in and out of government say no. These include a group of diehard nuclear opponents who view the risks of nuclear power as outweighing even the risks of climate change. Another group, probably larger, would prefer not to have to rely on nuclear and think the nation will be able to get by without it. These nuclear skeptics, who are well-represented in environmental advocacy organizations, are seriously concerned about the climate threat, but think that other low-carbon technologies such as solar and wind are either already adequate to the need or will soon become so. They point to the recent rapid declines in the cost of solar and wind technologies. They note that U.S. electricity consumption has not increased for a decade. And, given the safety, security, and economic challenges facing the nuclear power industry and the still-unresolved problem of spent fuel management and disposal, they see no contradiction in advocating for strong climate policies while looking forward to a nuclear-free energy policy.

The electric power companies are not much interested in nuclear innovation either. Many are preoccupied with the nearer-term challenges of distributed solar and wind technologies, microgrids, smart residential energy management systems, and the rise of a new class of distributed energy service providers. These new developments are destabilizing traditional utility business models and seem poised to account for a growing share of utility electricity markets. They have captured the attention of utility executives, who have already been forced to adjust to the implications of a decade of zero electricity demand growth.

But even as the challenge of distributed energy resources and a shrinking power market has transfixed the electric power industry, the next major challenge is looming just over the horizon and, paradoxically, it has many of the opposite characteristics. What the power industry has yet to fully recognize is that the most plausible pathway to achieving deep reductions in carbon emissions by mid-century will require major growth of electricity output. Moreover, this increased output will be needed even as the vast bulk of the nation's baseload generating capacity—comprising all of the coal plants and most of the nuclear plants, which together provide almost 60 percent of the current electricity supply and are the foundation of the reliability of the grid—will be forced to retire over the next 20 to 30 years.

Because it is more difficult to decarbonize liquid fuels and gas flows than electricity, achieving an 80 percent reduction in CO_2 emissions by mid-century implies almost complete decarbonization of electricity supplies along with the substitution of electricity or electricity-generated fuels for the direct combustion of fossil fuels in other energy markets. That means more use of electricity. How much more will depend on the future performance of the U.S. economy. This cannot be predicted, but it is to be hoped that recent history is not a reliable guide. Over the past decade, the nation's annual economic growth rate averaged a dismal 1.3 percent, compared with an average of 3.3 percent during the previous three decades. This is the main reason electricity consumption has not grown since 2005.

A period of stronger growth would be welcome. A careful recent study by the Deep Decarbonization Pathways Project estimated that if the U.S. economy were to grow at a somewhat more robust 2.5 percent per year through the year 2050, the 80 percent emission reduction target could be achieved at relatively modest incremental cost. But this would require aggressive improvements in energy efficiency, combined with a doubling of electricity use and a drastic reduction in the carbon intensity of the electric power system, to just 3-10 percent of its current level. That, in turn, would require eliminating essentially all coal and most natural gas from the electric power system, even as it doubled in size.

This, by the way, is the main reason natural gas cannot be the "bridge to a low carbon energy future" as suggested by some energy experts. It is true that the displacement of some coal by lower-cost natural gas in the electric power sector has been one of the main contributors, together with weak economic growth, to the recent decline in U.S. CO_2 emissions, which have fallen by about 10 percent since 2005. But if the rest of the nation's coal-fired power plants, which still account for 35 percent of electricity generation, were replaced by natural gas, total CO_2 emissions would decline by another 20 percent—an important result to be sure, but only a quarter of the overall reduction needed. And if the nation's fleet of nuclear power reactors was also replaced by natural gas, the additional CO_2 emissions that would result would offset more than half of those savings. (These additional roles for natural gas would also increase total U.S. natural gas usage by nearly 70 percent, inevitably putting strong upward pressure on natural gas prices.)

The truth is that neither the power industry nor the government has a plan for replacing the coal and nuclear plants that will be closed over the next 20 to 30 years. It is instructive to contemplate the vast physical scale of this task. If all the coal that is currently consumed in a single year in the nation's coal-fired power plants were loaded onto a single coal train, that train would be about 83,000 miles long. And all of that coal will need to be replaced, or the CO_2 captured, in order to meet the mid-century emission reduction target.

If the coal plants were replaced by, say, wind turbines, and the turbines were arranged in one long line (of course, they would not be) with the individual turbines spaced optimally, the line would be 135,000 miles long, even longer than the coal train. And if the coal plants were phased out over, say, 20 years, these wind turbines would need to be deployed at a rate of about 30,000 megawatts per year, which would be about five times faster than the average rate of wind turbine installation over the past decade. The requirement would be greater still if wind resources were also contributing to the expansion of the power grid during this period. Incidentally, the same thought experiment that produced the 83,000-mile-long coal train would yield a nuclear train just one mile long—the length of the train that could carry all the nuclear fuel assemblies needed to power all of the nation's 100 nuclear power reactors for a year.

ClimActs, *Climate Guardians*, 2015.

ClimActs is an Australian theater troupe using striking visual spectacle and satire to communicate the urgent need for the world to respond to climate change. The troupe's *Climate Guardians* use angel iconography to highlight the vital role of guardianship of natural resources in addressing the global threat from climate change. They staged several performances at iconic sites around Paris throughout COP21.

Indeed, extreme compactness is a major advantage of nuclear over renewable technologies, which must labor under the yoke of very low solar and wind energy densities. In addition, nuclear provides major environmental and public health advantages over coal and other fossil fuels. For example, since the early 1970s, nuclear power is estimated to have saved almost 2 million lives worldwide that would otherwise have been lost due to air pollution from fossil fuel combustion. Of course, nuclear power also has numerous drawbacks. But it is a matter of basic common sense that when faced with a task as vast and challenging as deep decarbonization, the more options that are available, the more likely the nation is to be successful. So, although it is an interesting academic exercise to think about whether a single option—wind or solar, for example—could do the trick, no sensible strategy would advocate this, especially given the potential consequences if that option should fail.

For the world as a whole, the case for keeping nuclear energy in the mix is stronger still. Most of the growth in energy demand over the next several decades will occur in the developing world, where governments and energy firms will face enormous difficulties in satisfying the aspirations of billions of people for higher living standards while meeting stringent carbon emission limits.

According to the International Energy Agency, a two- or three-fold increase in worldwide nuclear generating capacity will be needed by mid-century to achieve the carbon emission reduction consistent with holding the increase in the global average surface temperature to 2°C or less by century's end. But the world is far from achieving this. A few countries (most notably China, but also Russia, India, and Korea) have ambitious nuclear growth plans, and more reactors are in the construction pipeline around the world today than in many years (24 of the 67 reactors are in China). Several other countries, including Abu Dhabi, Vietnam, Turkey, and Bangladesh, have also embarked on new nuclear energy programs, and others are seriously considering doing so. But several advanced countries are backing away from nuclear, including Germany, Italy, Switzerland, and Sweden, and the future of the large Japanese nuclear program hangs in the balance.

When all of these national plans are aggregated and combined with the expected retirement of much of the existing global nuclear fleet as those plants reach end of life (they are already about 30 years old, on average), the projected nuclear contribution to global carbon mitigation falls far short of the projected need. Indeed, the share of nuclear in global energy output seems as likely to shrink as to grow.

Closing the gap

This gap between plans and need is an uncomfortable reality for advocates of a larger nuclear role. How could it be closed? Some observers predict that this will happen with today's nuclear technologies, once the full costs of burning fossil fuels, including the environmental costs of carbon emissions, are charged to energy users. But nuclear innovators believe that nuclear energy technology will itself need to be made more competitive if its potential is to be fully realized.

A key question, then, is what should be the government's role in future nuclear innovation? For many decades, the main objective of government-funded nuclear R&D around the world was to extend the uranium resource base. And the main focus was on the development of breeder reactors to achieve this. Today, though, other goals are far more important: reducing costs; increasing safety; reducing the burdens of nuclear waste disposal; controlling the threat of nuclear terrorism; making the siting of nuclear facilities easier; and reducing nuclear lead-times, which have become excessive in many parts of the world and are adding cost, reducing flexibility, and exposing investors to greater risk.

Nobody can say for sure which technologies are best suited to solving these problems, or whether the future nuclear power industry will be dominated by descendants of today's LWRs or the offspring of other reactor technologies now under development. Indeed, nobody knows whether there will be a single, dominant nuclear technology or whether multiple technologies will co-exist, optimized for different segments of a global market that, later in the century, might include a Chinese power grid several times bigger than the U.S. grid today; an East African grid serving, say, Kenya, Tanzania, and Uganda that is currently about 500 times smaller; and a host of non-grid applications, such as water desalination, industrial process heating, and fluid fuels production.

The total cost of commercializing a new nuclear technology could easily exceed $10 billion. Funding even one such effort in the federal budget would almost certainly be too costly in the current fiscal environment. Funding several of them this way would be out of the question. So the focus must shift to private investment. It is easy to dismiss this possibility given the long lead-times and high risks of commercializing nuclear technology. But private investors have already shown more interest in funding early-stage nuclear development than almost anyone expected. Thus, instead of asking which technologies the government should be developing, a better question at this stage is how the government—in pursuit of its climate policy goals—can reduce the risks and increase the returns to private nuclear developers.

In answering this question, there are three different timeframes to consider. The first—what can be called *Nuclear 1.0*—is the period through about the year 2030, when the focus must be on innovations to reduce the cost of operating and maintaining the existing fleet, making it more likely that plant lifetimes will be extended. The second and even more important timeframe is the period beginning in about 2030, when large-scale retirements of coal and nuclear plants will be well under way (*Nuclear 2.0*). The focus here must be on commercializing advanced nuclear reactors and fuel-cycle technologies that can meet one or more of three goals: replace the conventional baseload capacity; compete effectively in power grids that by then will have much larger amounts of intermittent renewable capacity, as well as more technology-enabled autonomy for electricity users; and make possible the penetration of nuclear power into a broader range of energy markets, including industrial processing, desalination, and transportation fuels production. The third timeframe, (*Nuclear 3.0*) is after 2050, when more advanced nuclear technologies may be needed to bring down carbon emissions even further.

What would be the government role in each case?

Nuclear 1.0 (2015-2030). Many of the most important actions the government can take to extend the life of the existing nuclear fleet are not innovation-related at all. For example, as long as wholesale electricity markets do not attach a value to the reliability that nuclear plants provide to the grid, which is the case in much of the country, nuclear will be at a competitive disadvantage relative to wind and solar, whose intermittency exacts a cost on the rest of the system. Electricity market rules are mainly determined at the state level, but the federal government can influence outcomes. Another needed policy correction concerns state and federal incentives for investment in low-carbon electricity generation, which also seem skewed against nuclear. The most sensible approach would be to impose a uniform price on all carbon emissions, most likely through a carbon tax.

In the absence of this, there is the Obama administration's Clean Power Plan. This plan creates financial incentives for investment in new wind and solar capacity to displace fossil fuel generation, but provides no incentives for utilities to invest in extending the life of their existing nuclear plants, even though the investment required per unit of low-carbon electricity will typically be far smaller, and even though the nuclear plants today provide about five times more low-carbon electricity than the contribution of wind and solar combined. What is worse, in some states the Clean Power Plan creates perverse incentives for nuclear plants to be closed and replaced by new natural gas plants, which, of course, will emit additional amounts of CO_2.

This is not good public policy, and if the Environmental Protection Agency, which administers the Clean Power Plan, cannot correct it, the government should instead create other incentives for utilities to keep their nuclear plants going, such as a production tax credit for plants whose licenses have been extended, similar to that provided for new wind turbines. Another helpful federal action would be to reactivate the government's spent fuel management and disposal efforts, which have been largely dormant since the decision several years ago to stop the licensing review for the Yucca Mountain nuclear waste repository.

There are also technical opportunities to reduce the cost of operating and maintaining the nuclear fleet as it ages. These would include, for example, measures to prevent or slow corrosion; networked sensors enabling more efficient monitoring of plant conditions; new, more cost-effective physical security technologies; and business model innovations to reduce costs. Most of the

R&D to exploit these opportunities should be done by the utilities and their suppliers, and the most important role of the government would be the policy measures described previously, since their impact would be to increase the returns to these R&D investments. But government laboratories also have a useful role to play in support of this innovation agenda.

Nuclear 2.0 (2030-2050). The highest priority of nuclear innovation policy should be to promote the availability of advanced nuclear power systems 15 to 20 years from now. This is not currently a goal of U.S. policy, and it will seem unrealistic to many, but that is because pathologically long lead-times of all kinds in the nuclear industry have become the norm. The original LWR technology was commercialized in about half the time. Of course, there is no Admiral Rickover today, and the federal government is hamstrung in ways that congressional legislators of the 1950s and '60s could not have imagined. But in other respects, the environment is more favorable for faster development. Dramatic improvements in data and in modeling and simulation of nuclear power plant behavior, enabled by new generations of supercomputers, are making possible much faster, more efficient, and more accurate approaches to design, new materials development, and analysis, while new modular construction techniques have the potential to shorten project lead-times greatly. There are several development groups, some of them led by private U.S. interests, others based overseas, that could put forward a credible plan for commercializing their technologies on a 15- to 20-year timeframe under the right conditions.

The role of the federal government should be to create an environment in the United States that could attract and encourage such groups. This would involve:

- Providing sites and facilities at one or more national nuclear laboratories for testing, prototyping, and conducting precommercial demonstrations.
- Opening up these capabilities to both domestic developers and qualified development groups based overseas.
- Providing adequate funding for the NRC to address the regulatory issues raised by innovative designs in a timely way.
- Enacting administrative reforms that would establish a staged licensing process, with clear and well-defined interim approval milestones and increasing levels of review at each stage from pilot scale to full commercial deployment, allowing developers to take graduated investment risks.
- Promoting organizational reforms at the NRC, most importantly by establishing a regulatory

Sterling Ruby, *Black Stoves,* 2015.

Sterling Ruby's *Black Stoves* installation features a series of outdoor woodstoves that are regularly fed with logs to heat the atmosphere needlessly, representing humans' environmental carelessness. It is on view through February 14, 2016, in the courtyard of the Museum of Hunting and Nature, Paris. Photograph by Robert Wedemeyer, courtesy of Sterling Ruby Studio and Gagosian Gallery.

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"skunk works"—a separate unit responsible for regulatory development and licensing of innovative nuclear technologies, with a small staff of highly capable experts dedicated to working out nuclear safety requirements collaboratively with nuclear developers. (This unit would preferably be located far from NRC headquarters and would surely attract some of the NRC's best engineers).

- Providing financial incentives designed to encourage a more decentralized strategy for nuclear technology scale-up, demonstration, and early adoption, with a greater role for interested states and regions and a new kind of partnership between the federal government, the states, and private innovators and investors.
- Convening an International Nuclear Safety Evaluation, with the goal of establishing safety requirements for the next generation of reactors capable of achieving expected safety levels an order of magnitude beyond the level of today's most advanced reactors.

In this new policy environment, a government agency would not do what the Department of Energy and its predecessors have tried so often to do in the past: choose the next nuclear technology. But the government would still need to make choices about which development groups merited its support. It ought to be guided in these choices by an independent advisory board with the knowledge and experience to judge whether developers have credible technical, management, and financial plans in place that would give them a reasonable chance of achieving commercialization in the 2030–2040 timeframe.

Nuclear 3.0 (after 2050). On this timescale, the government must play the lead role. In recent years, budget pressures have narrowed the scope of long-term nuclear energy research, which is now dominated by the U.S. participation in ITER, the international tokamak fusion project that is under construction in France. Congressional support for ITER has wavered in the face of project delays and cost overruns and as promising alternative pathways to commercial fusion have opened up. The estimated lead time of 30 to 40 years for commercialization of tokamak technology has also sapped enthusiasm for this program. From a climate policy perspective, the best way to view the development of such long lead-time technologies is as an insurance policy—an option that may be needed if nearer-term low-carbon technologies lose their viability or fail to materialize at all. As with any other kind of insurance, the best policy in this case is the one that can be purchased at lowest cost with the highest likelihood of being available if needed. A careful assessment of the range of technological pathways to commercial fusion is now needed to design a long-term nuclear energy R&D portfolio that would have these characteristics. This assessment should probably also include promising nuclear fission technologies that could not "make the cut" for Nuclear 2.0.

Time for a clear departure

This new nuclear innovation agenda would be a clear departure from more than three decades of controversy, timidity, and indecision in U.S. nuclear energy policy. During this period, the nation's nuclear industry has lost ground to its international competitors, and U.S. influence over the international nuclear security regime has waned. It is one of the unfortunate legacies of the years of policy drift that now, at the very moment that climate concerns are building and the need for new sources of low-carbon energy is growing more urgent, the ability of nuclear energy to respond to this need is in doubt.

But a new generation of nuclear technologies holds promise of reversing this decline. The outcome is far from certain, but no worthwhile innovation initiative ever is. Moreover, the need for nuclear innovation is global, since the current generation of nuclear technologies is struggling to compete with fossil fuels in much of the rest of the world, too. The innovation roadmap sketched here has the potential to restore U.S. leadership in a field that, notwithstanding the hopes of many environmental activists and the gloomy prognostications of some pundits, is most likely still in the early stages of development. After all, it is often forgotten that the first practical demonstration of nuclear fission came just 16 years before a similar milestone for the first solar photovoltaic cell, which is still widely considered "new" technology.

So the United States now has a clear choice to make. The nation can decide to be one of the world's leaders in shaping the next generation of nuclear energy technologies, or it can decide to stay on its current path and become a 21st-century nuclear also-ran. Given the stakes involved—the economic opportunity, the implications for nuclear safety and security, and the climate threat—there is really only one option.

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Box: The Nuclear Innovation Agenda

Which innovations will be most influential in expanding the global market for nuclear energy?*

Institutional innovations are an important part of the answer. The most striking lesson of Fukushima, as well as Chernobyl and Three Mile Island before it, is that what might otherwise have been serious but manageable accidents were transformed into disasters by multiple failures of governance. What is needed to correct these failures is well understood. It includes transparent decision-making processes, independent regulatory bodies, and the need to build and sustain a safety culture in nuclear operating organizations. In the U.S. significant progress has been made in each of these areas since the Three Mile Island accident. But this vital work is never complete, and for nuclear energy to expand around the world more-capable nuclear governance institutions – especially international institutions – will be essential. Building these will require a high level of organizational and political innovation.

Technical innovations will be even more important, partly because they will reduce the burden on nuclear institutions. A key trend is to rely more heavily on passive design features to prevent nuclear malfunctions, instead of depending on active engineered safety systems and accurate interventions by human operators. The latest generation of light water reactors has moved in this direction, but newer concepts go much further toward the goal of 'walkaway safety' – so-called because in any conceivable accident scenario reactor operators could simply walk away and let the reactor shut itself down and cool itself off on its own, without the risk of fuel overheating and without the threat of an offsite radiation release. Such reactors could be built today, and it does not seem unlikely that the goal of walkaway safety could become a regulatory requirement for all power reactors a few decades from now.

One of the keys to improving economic competitiveness will be to reduce cycle times in the nuclear industry. Less ponderous regulatory processes will help, but there are also opportunities for technically-driven cycle time reductions. For example, rapid advances in modeling and simulation of reactor neutronics, thermal hydraulics, and nuclear fuel behavior enabled by new generations of supercomputers are making possible much faster and more efficient approaches to reactor design. New modular fabrication and construction methods promise to shorten construction times, as do smaller reactor designs, whose benefits may also include reductions in capital-at-risk, faster learning cycles, and better matching with small power grids, which would make such reactors well-suited not only to many new nuclear countries, but also to many nuclear operators in mature nuclear states.

Other innovations are designed to make reactor siting easier. Gas-cooled and molten-salt cooled reactors, which operate at much higher temperatures than LWRs, require far less cooling water, and may even be cooled by air, creating new opportunities for siting in arid inland regions. Nuclear plants mounted on double-hulled floating platforms, built in shipyards and towed to locations several miles offshore in relatively deep water and connected to land by an underwater transmission line, would be unaffected by earthquakes or tsunamis. Shipyard fabrication could be expected to reduce construction lead-times, and at end of life the plants would be towed back to centralized shipyards for decommissioning, with the offshore mooring immediately returned to 'greenfield' conditions.

Longer-term possibilities include lifetime fueling of reactor cores – the 'nuclear battery' concept – in which fuel charged to the core at the start of operations would not need to be removed until the end of life, an innovation that would help to reduce proliferation risks. Some reactors could be optimized for burning nuclear waste,

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transmuting the longest-lived isotopes in the waste into short-lived species. Another possibility would be integrated power plant-waste disposal systems, with spent fuel never leaving the power plant site and disposed of directly in modular deep boreholes several miles below the earth's surface in the stable, dry bedrock that is abundant in most countries. Deep borehole disposal technology draws on the enormous base of related know-how in the oil and gas sector, and may be especially suitable for nations with small nuclear programs as well as densely-populated island nations in seismic regions, like Japan and Taiwan. In the longer term, advances in computational power and new tools for materials synthesis may one day make it possible to design and build radiation-resistant materials from the ground up, atom by atom, yielding ultra-secure nuclear waste materials with lifetimes of tens of thousands of years.

Other kinds of innovations will be needed to respond to the rapid evolution of power grids and power markets, which over the next couple of decades are likely to undergo technical and institutional changes more far-reaching than any in the previous 100 years. Further penetration by non-dispatchable solar and wind generating technologies will occur, both at utility scale and in smaller-scale decentralized deployments, as well as new roles for intelligent grid technologies, local microgrid operating systems, web-connected electrical devices, and large-scale data analytics. The challenge will be to work out how to meet rapidly varying electrical loads affordably and reliably with low-carbon power systems that will eventually consist mainly of reliable, dispatchable nuclear and non-dispatchable renewable capacity. In these new conditions, conventional base-load nuclear power technologies will need to be augmented by new, more flexible alternatives -- for example, hybrid nuclear/renewable systems, with the nuclear plant capable of switching between selling electricity directly and producing storable fluid fuels depending on price conditions.

Another example is the nuclear air-Brayton combined cycle system under development at MIT and Berkeley, in which a high-temperature nuclear heat source – in this case a fluoride salt-cooled reactor -- is integrated with large-scale thermal storage and advanced fast-response turbines to meet peak demand, with the additional capability to produce high-temperature process heat when electricity prices are low.

Not all of these innovations could be developed in time to meet the Nuclear 2.0 requirement in the 2030s, and some may never materialize at all. But the need for a new generation of nuclear technologies capable of competing with fossil fuels has never been greater, and it is time to remove the barriers that for too long have blocked the path of nuclear innovators in the U.S.

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* *Because of space constraints, this box did not appear in the published version of the article.*