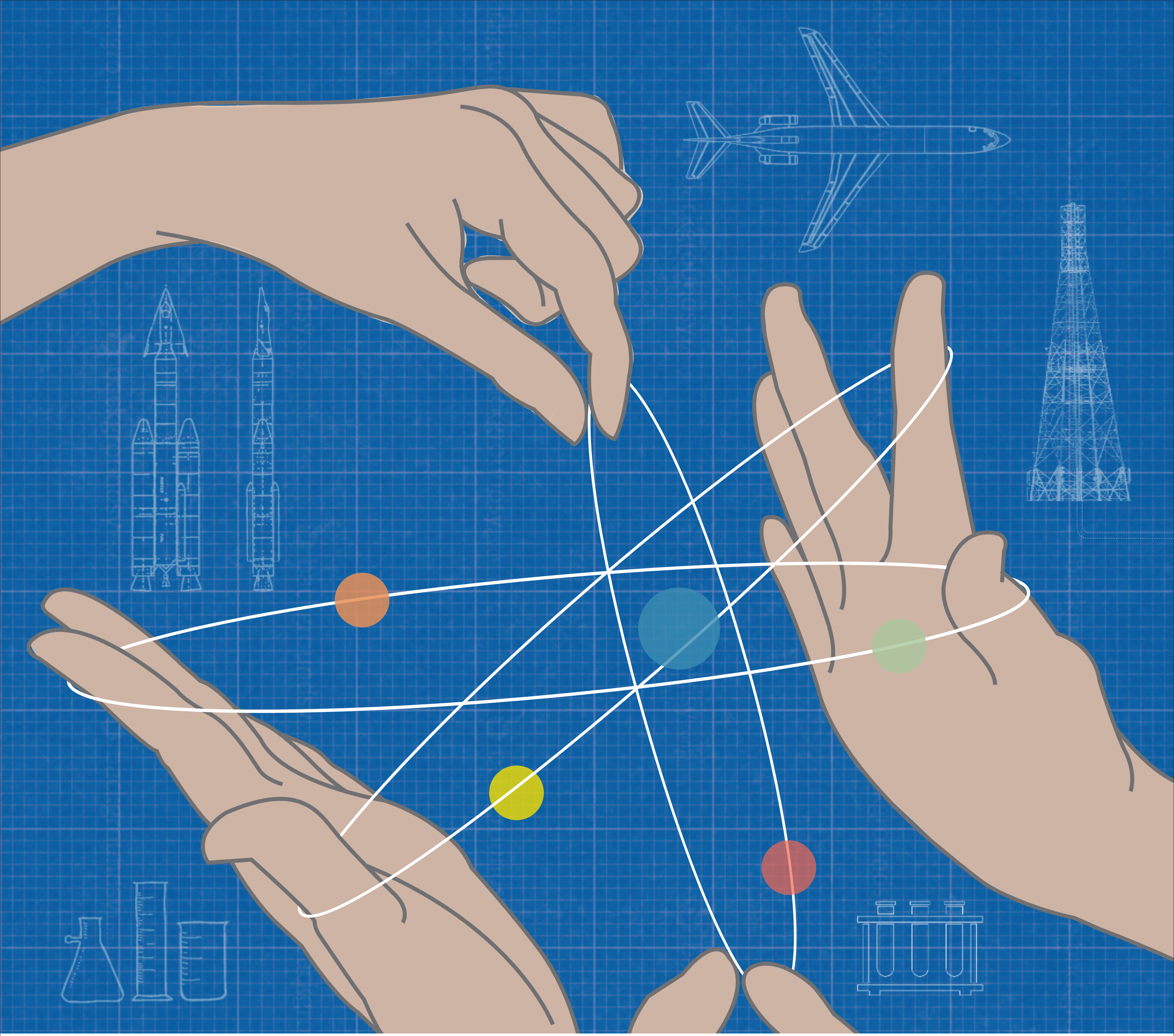


HOW TO MAKE NUCLEAR INNOVATIVE

LESSONS FROM OTHER ADVANCED INDUSTRIES

BREAKTHROUGH INSTITUTE

JESSICA LOVERING, LOREN KING
AND TED NORDHAUS

HOW TO MAKE NUCLEAR INNOVATIVE

LESSONS FROM OTHER ADVANCED INDUSTRIES

JESSICA LOVERING, LOREN KING
AND TED NORDHAUS

ABOUT THE AUTHORS

JESSICA LOVERING is the Energy Director at the Breakthrough Institute.

LOREN KING is an economist at the Institute for Public Policy Research (IPPR).

TED NORDHAUS is the Executive Director at the Breakthrough Institute.

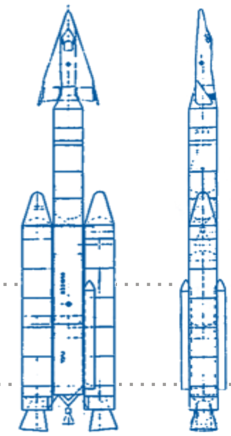
The Breakthrough Institute is a leading global research center that leverages high-quality scholarship to identify practical solutions to major environmental and human development challenges.

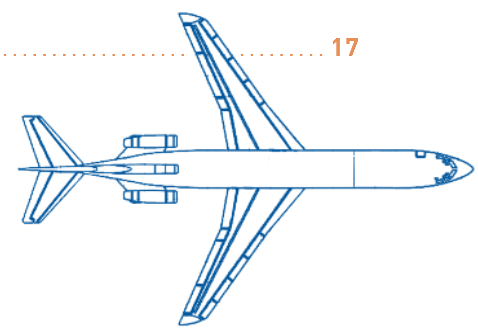
www.thebreakthrough.org
www.facebook.com/BreakthroughInstitute
@TheBTI

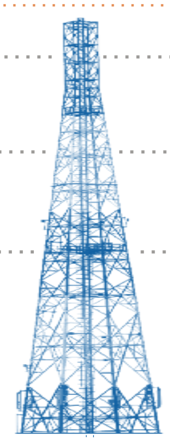
BREAKTHROUGH INSTITUTE

MARCH 2017

TABLE OF CONTENTS







EXECUTIVE SUMMARY

If the nuclear industry once stood at the forefront of energy innovation, it is today rapidly losing ground. Global nuclear generation has fallen 9% since its peak in 2006, with closures outpacing new builds in many developed economies, and fossil fuels still cheaper and faster to deploy across the developing world. Even as climate change emerges as one of this century's defining challenges, nuclear's share of global electricity is declining.

The next generation of nuclear plants holds promise to be cheaper, safer, more flexible, and faster to build than the current fleet. But the old model of innovation—state-led and top-down—stands in the way of commercializing such technologies. Dozens of advanced reactor projects in the United States and Europe have languished over the last 40 years; experimental projects across Asia, meanwhile, continue to depend on an outdated model of innovation. In order for new designs to meet the needs of deregulated markets in developed countries, and to outcompete cheap fossil fuels in the developing world, the nuclear industry will need to innovate in step with its technologies.

Doing so will require far-reaching changes to the nuclear industry itself, and to the public institutions, policies, and regulations designed to support it. To date, the nuclear industry has succeeded in making incremental improvements to large light-water reactor designs, resulting in reactors that operate more safely and at close to full capacity. While this model was once sufficient to support the development and growth of the industry, it has proven unable to support the kind of far-reaching technological innovation the sector now needs to compete with adjacent energy technologies.

A highly innovative nuclear sector will require tilting the playing field away from large, incumbent nuclear firms and toward smaller, more entrepreneurial start-ups. With its growing ecosystem of advanced nuclear companies, world-leading nuclear engineering programs and national laboratories, and extensive venture capital networks, the United States is well positioned to lead such a shift. Nevertheless, considerable barriers stand in the way of the development of an innovative advanced nuclear industry. Transformation of the industry will require significant policy reform.

The prospect of disruptive innovation within a highly complex technology industry, fortunately, is not without precedent. In this report, we examine four advanced industries with strong records of innovation: wide-body aircraft, pharmaceuticals, commercial spaceflight, and unconventional gas extraction. Each sector offers the nuclear industry its own lessons for developing and commercializing radically new technologies—the aviation industry, for instance, demonstrates the importance of smaller designs that allow for economies of multiples as well as stable demand. The recent transformation of biotech attests to the need for a diverse mix of firms and a staged licensing process. Commercial spaceflight, meanwhile, shows the benefits of an explicit shift to private-sector-led innovation, while the success of hydraulic fracturing owes much to the close collaboration of public and private organizations.

Based on these case studies, we draw a number of recommendations for modernizing nuclear innovation in the United States, including:

1. LICENSING REFORM. Licensing of new nuclear technologies will need to be reformed in order to support smaller, entrepreneurial firms and to build investor confidence as key design and testing benchmarks are achieved.

2. PUBLIC-PRIVATE PARTNERSHIPS. National laboratories will need to provide private companies with access to equipment, technical resources, and expertise in order to lower costs and promote greater knowledge spillover in the testing and licensing process.

3. TARGETED PUBLIC FUNDING FOR R&D. Significant and sustained research funding should be directed toward solving shared technical challenges.

4. INTER-FIRM COLLABORATION. Policy and funding should be designed to encourage knowledge spillover and collaboration between companies.

5. PRIVATE-SECTOR LEADERSHIP. Public investment in demonstration and commercialization should follow private investment and avoid early down-selection of technologies.

Together, these changes would entail a reorganization of the nuclear sector that would be both far-reaching and long overdue, one that would drive the development and deployment of advanced nuclear reactors through bottom-up innovation, private-sector entrepreneurship, and targeted public investment. Without remaking the nuclear sector in this way, prospects for the sort of disruptive innovation that would assure nuclear energy an important role in the global energy future appear unlikely. There is unlikely to be a 21st-century nuclear renaissance without first creating a 21st-century nuclear industry.

INTRODUCTION

By most metrics, the development and deployment of nuclear power ranks as one of the most successful energy transitions of the last century.[1] In the course of 40 years, between 1957, when the first commercial nuclear reactor came online, and 1997, the world deployed 340 GW of nuclear capacity,[2] and nuclear energy grew to account for close to 20% of global electricity generation.[3] Nuclear grew from 1% to 5% of global energy consumption in just 13 years, a feat that took petroleum over 15 years; hydroelectric and natural gas took closer to 40 years to grow a similar share.[4]

But recent decades have brought a change of fortune for the global nuclear industry. While 2015 and 2016 saw more new nuclear power capacity come online than at any time since the early 1990s,[5] new builds have still been outpaced by retirements and premature closures in recent years.[6] Total nuclear generation peaked in 2006 worldwide and has since fallen 9%,[7] primarily due to the temporary closure of Japan's entire nuclear fleet but also due to permanent closures in Europe and the United States.[8] Nuclear's share of global electricity peaked a decade earlier, in 1996, at 18% and has since fallen by almost half to only 11%.[7] Even in Asia, where there has been a boom of new construction—20 reactors under construction in China alone—nuclear generation has only barely managed to keep pace with fossil fuel additions.[9]

There are many reasons why nuclear deployment has stalled in recent decades. Slow electricity demand growth, rising construction costs, liberalized electricity markets, and exaggerated public concerns about the risks associated with nuclear power have brought new nuclear construction to a halt in most developed nations.[10] Emerging economies such as China and Korea have succeeded in building out significant nuclear fleets in recent years at low cost.[11] But cheap fossil fuels, together with poor institutions, technical capabilities, supply chains, and the absence of skilled labor, have limited nuclear deployment in developing nations more broadly.[12]

While economics alone cannot account for stalled nuclear deployment, the comparatively high capital costs associated with building large light-water reactors have without question played a significant role. Rising costs are not intrinsic to nuclear energy technologies. In a 2016 study published in *Energy Policy*, we demonstrated that some countries have been able to minimize nuclear cost escalation, or even bring costs down, through a mix of reactor standardization, state control of reactor development and utilities, and multiple-reactor sites.[2] However, high construction costs, in combination with other social and institutional factors, suggest that a nuclear renaissance—deploying new reactors at historic levels or at the rate required to mitigate climate change—appears unlikely so long as doing so primarily entails the deployment of large light-water reactors.[13]

Without a new generation of nuclear plants that are cheaper, more flexible, and faster to build than reactors operating today, it appears likely that the nuclear sector will continue to struggle in most parts of the world. This is especially the case in the United States, where the sort of state-led, standardized deployment of nuclear reactors that has characterized the build-out of large nuclear fleets around the world over the last three decades appears highly unlikely.[14]

Nuclear deployment will need to shift from large public infrastructure projects to a fully manufactured plug-and-play product. Innovative designs will need to be simpler and faster to build and require much less human labor to construct and operate, with fewer active safety systems and without large and costly containment systems.[14] New nuclear reactors will need to be designed to meet the demands of the market and the customers who will buy them: namely utilities, but also industrial energy consumers and large commercial enterprises that require large-scale, reliable heat and power.

In our 2013 report *How to Make Nuclear Cheap*, we identified attributes of advanced nuclear technologies that would lead to dramatically cheaper and more scalable power plants: passive safety, modularity, efficiency, and technological readiness (including a mature supply chain).[14] Currently, there are a large variety of experimental reactor projects ongoing across Asia that could meet some or all of these criteria.[15] But like the dozens of advanced reactor projects in the United States and Europe that were built and abandoned during the last 40 years, these programs still follow the old nuclear innovation model, characterized by heavy state support and early top-down selection of technology..

In this report, we argue that a step change in nuclear technology will require a corresponding step change in the structure of the nuclear industry and the public institutions, policies, and regulations that support it. The old model of commercialization of nuclear technologies, which relied on heavy state support and centralized decision-making, simply hasn't delivered new designs that meet the needs of deregulated and competitive markets in the developed world, or that can compete with cheap fossil fuels in most developing countries.[16]

In the United States today, there are dozens of advanced nuclear start-ups[17] that could bring game-changing nuclear technologies to market. But the path to commercialization for these designs remains uncertain. The Nuclear Regulatory Commission is presently unprepared to license them. The Department of Energy and the National Laboratories are not well set up to assist them. Nor are all but the largest incumbent nuclear firms in position to acquire the large amounts of capital that would be required to navigate the current licensing process, develop advanced materials and fuels, or build first-of-kind reactors.

To succeed, the industry will need to evolve to become more like other innovative technology sectors, characterized by networked, bottom-up innovation, public-private partnerships to solve key technological challenges, and open and benchmark-based competition for public investment. Other large, complex industries have been more successful in bringing innovations to market and in some cases have, with support from government, done so by remaking the structure of their industries.

In this report we consider the historical, structural, and economic factors that have hindered innovation in the nuclear sector. We conduct case studies of four complex, highly regulated technology industries—commercial aviation, pharmaceuticals, spaceflight, and shale gas—that have successfully brought disruptive innovations to market and consider what lessons might be learned that could be applied to the nuclear innovation system. How do these sectors engage with their regulators, and what is the structure of regulation? Does the government support innovation directly or indirectly, and how do they incentivize private R&D? What is the structure of public-private partnerships, and how effective have they been? Finally, we offer a range of policy recommendations that we conclude would greatly increase the likelihood that new game-changing nuclear technologies might become available commercially in the next several decades.

THE LAY OF THE LAND: FROM CRISIS TO OPPORTUNITY

THE LIMITS OF LIGHT-WATER REACTORS

Impressive as the global build-out of nuclear energy has been over the last half-century, there are good reasons to think that existing light-water reactor technologies are unlikely candidates for a significant global build-out today. Experience with large public works projects in both developed and developing economies in recent decades suggests that costs have become difficult to contain.[18] Liberalized electricity markets in developed economies where demand is growing slowly are a strong disincentive to invest in costly infrastructure that will operate for 60 to 80 years, even if the full life-cycle cost of those plants is relatively low. Many developing economies, where most growth in electricity demand is expected to come from, have neither the regulatory institutions, the infrastructure, nor the technological capabilities to build or operate large, complex nuclear plants that must be actively monitored and operated 24/7.[12]

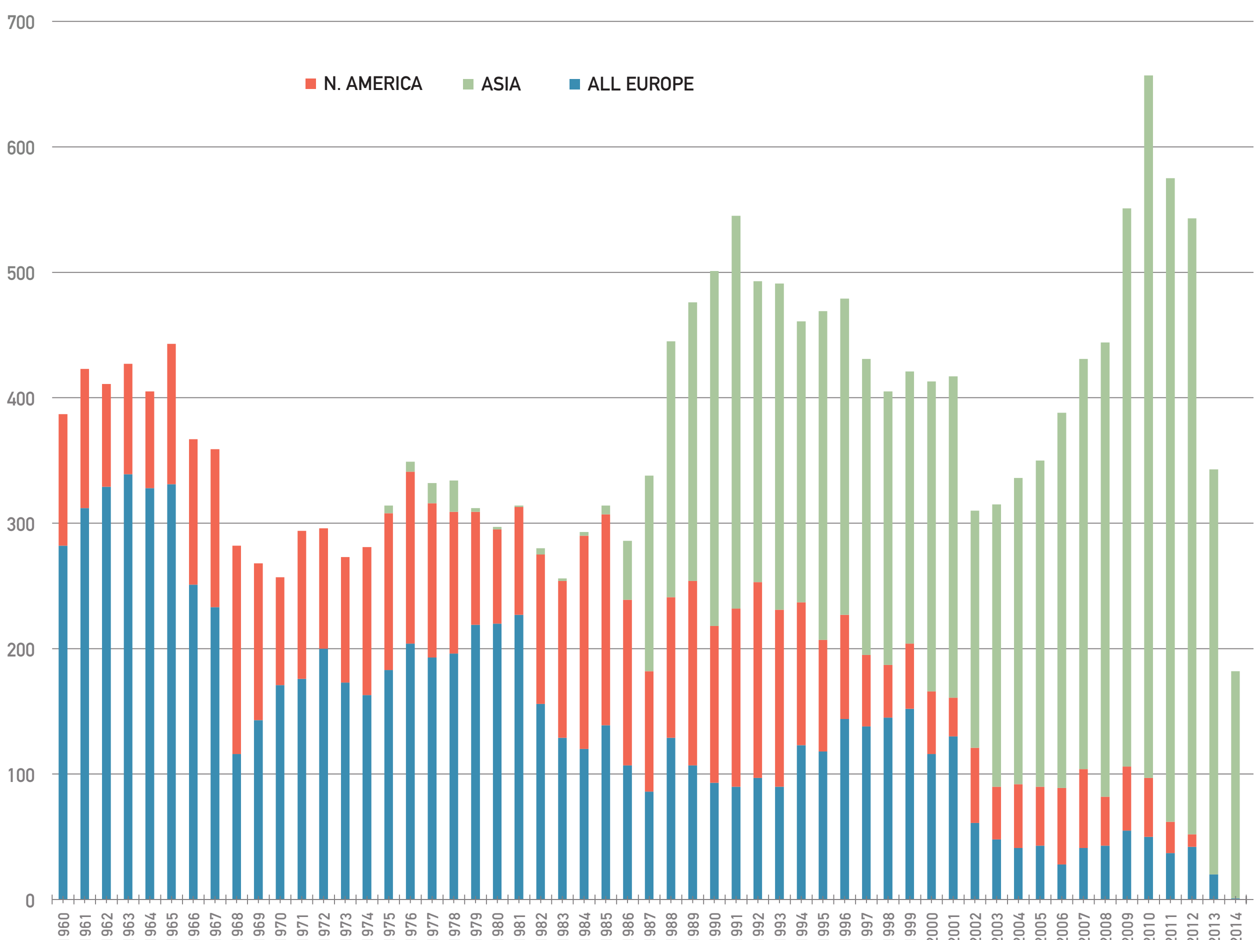


FIGURE 1. Nuclear patents in OECD countries. Note the shift from the United States, France, and Germany to Japan and Korea. Data from the European Patent Office's PATSTAT database.

While the United States has four reactors under construction, there are no concrete plans for new construction after those. And these four new reactors will not even be enough to offset the premature and planned closures of existing nuclear reactors before 2018, meaning the share of nuclear power on the US grid will be declining.[19] A similar story can be told elsewhere in the Western world, where precious few reactors are being built or planned.[13] What is more concerning: those reactors currently under construction, whether in the United States, Finland, or France, are behind schedule, over budget, or both.[20,21]

As economic and political headwinds to new nuclear energy have grown in developed economies, nuclear deployment and development have shifted from the West to the East. Since China completed its first nuclear power plant in 1991, it has become the principal builder of new plants and accounts for a third of reactors under construction currently.[22] The Chinese government, along with those of South Korea and Russia, has committed to deploying its nuclear technology across the world.[23] Russia has already built (or is planning to build) reactors in 13 countries,[24] while South Korea announced that it would aim to export 80 reactors by 2030.[25]

The geographic shift in nuclear deployment has brought with it a corresponding shift in nuclear patenting. In Figure 1, we can see the changing proportion of nuclear patenting by country, with Asian countries, primarily Japan, China, and South Korea, coming to dominate.[26]

STATE-OWNED INNOVATION

While the geography of nuclear development has shifted, there hasn't been much evolution of the nuclear innovation system anywhere in the world. Whether it is China, Russia, or South Korea, all of these countries have anchored their nuclear development around three pillars: state-owned utilities, currently or formerly state-supported nuclear vendors, and large public R&D and deployment programs (with a strong central government behind them).

In China, electricity production and nuclear development are heavily supported by the state. Up until 2002, a state-owned utility owned 46% of the power generation assets across China, but was broken up into 11 smaller municipal utilities.[22] Similarly, nuclear power development was controlled by a state-owned entity, the China National Nuclear Corporation, until 1998 and is now managed by a suite of state-owned entities from the China State Power Corporation, State Power Investment Corporation, State Nuclear Power Technology Corporation, China Power Investment Corporation, and China General Nuclear Power Group.[27] In 2014, the government directed these various companies to form the China Nuclear Industry Alliance, to help them better cooperate and compete as a harmonized unit in the export market.

South Korea benefits from having a single utility operating all its nuclear power plants: Korea Hydro and Nuclear Power Co., Ltd., which is a wholly owned subsidiary of its national utility KEPCO that develops new nuclear reactor designs.[28] As in the case of South Korea, Russia's nuclear efforts are led by a single state-backed entity, Rosatom.

In all three countries, nuclear development and deployment has been state-led and directed to serve important geopolitical objectives, with significant implications for corresponding nuclear innovation investments. China's primary focus on the power side, since Areva built its first reactor in 1991, has been to develop a domestic Chinese reactor and indigenize its nuclear supply chain.[22] For this reason, China has historically spent 85% of its R&D funding on development, with over 80% of the R&D funding coming from industry.[29] In the United States, only about 50% of federal R&D goes to development,[30] and if you include private R&D, the share climbs to 63%.[29]

Like China, Russia and South Korea's innovation programs are heavily centralized, with targets and goals set by government agencies and performed at state-owned facilities. South Korea's R&D budget remains quite small; it spent roughly $133 million (US dollars) per year on nuclear fission R&D over the last decade, about 5% of Japan's annual fission R&D budget over the same time period.[31] The focus of Korea's nuclear program was initially to develop a low-cost domestic reactor and indigenize its nuclear supply chain,[2] and then to concentrate expertise on deployment of that technology in export markets.[32] Russia has also continued to build nuclear plants and export nuclear technology, since the state has sustained its commitment to nuclear development.

These countries' current efforts are not only broadly similar to one another but also to the early efforts of France, the United States, and Japan. In every case, the early development of civilian nuclear energy was primarily state-driven and centralized. In the United States, the first commercial demonstration was a reactor originally designed for naval aircraft carriers, developed at Bettis Atomic Power Lab in Pennsylvania.[33] Following this, Congress authorized funding for about a dozen demonstration reactor projects. When the government eventually got out of the commercial light-water reactor business, it allowed private companies to build designs closely based upon military technology, while also continuing to fund advanced research at the national labs.[34] The Atomic Energy Commission oversaw all aspects of nuclear, from weapons material and safety to research and development.[35] However, there was strong opposition to public power, which meant that the AEC was not able to fund full-scale nuclear power plant projects.[34] Civilian reactor development was only 2% of AEC's budget,[35] but it maintained control over the research agenda for advanced reactors. Non-LWR reactor development continued at the national labs and at demonstration plants, but funding gradually dwindled and individual projects were cut at the whims of successive presidents or AEC chairs.[35]

Outside of the United States, Canada, the United Kingdom, and the Soviet Union, most countries began their civilian nuclear programs by importing a design from an established nuclear country.[2] These countries then worked to indigenize the design, and R&D programs were focused on these efforts. While many of these countries pursued research and development of advanced reactors, the diversity of designs was limited. Large state-funded programs for non-LWR designs tended to focus on liquid-metal fast-breeder reactors, as they were thought to allow more sustainable use of uranium and thus provide cheaper nuclear electricity in a world with scarce uranium supplies.[36]

In France, the state-owned Electricité de France (EDF) started building gas-cooled reactors in 1955,[37] while the state-owned Atomic Energy Commissariat (CEA) was in charge of reactor development. In 1958, engineers from several French and American companies, including Westinghouse, founded the company Framatome (now Areva). They were focused on developing pressurized water reactors (PWRs) based on the Westinghouse design. Further development was focused on scaling up PWR technology in successive waves called "paliers."[38] EDF continued to build standardized reactor designs from CEA through the 1960s and '70s. France's centralized utility and reactor development, standardized design, and proactive government resulted in very low and stable construction costs compared to many other global nuclear fleets.[2]

The first commercial reactor built in Japan was a British gas-cooled reactor, followed by a fleet of American light-water reactors in the 1960s.[2] In the 1970s, the major Japanese manufacturing firms—Mitsubishi, Toshiba, and Hitachi—took over construction of nuclear power plants, but the designs were still based on foreign designs: boiling water reactors (BWRs) by GE and PWRs by Westinghouse. Backed by significant public R&D and a supportive regulator, these firms eventually built 30 of their own indigenous PWRs and BWRs from 1980 to 2007.[2] The Power Reactor and Nuclear Fuel Development Corporation continued research of heavy-water reactors, fast-breeder reactors, and advanced fuels like MOX.[39]

The similarities between present nuclear development efforts in China, South Korea, and Russia and early efforts in the United States, France, and Japan suggest that the basic framework for nuclear development and innovation has seen little evolution since the dawn of the nuclear age. The nuclear innovation model has been top-down and state-led, with public-sector scientists and policymakers selecting nuclear reactor designs early in the development process. These choices were based upon a range of geopolitical and economic considerations, and government laboratories and large, incumbent industrial firms worked together to demonstrate and commercialize a single, large-scale nuclear technology that would only be used for electricity production.[34]

THE BENEFITS AND LIMITATIONS OF TOP-DOWN INNOVATION

The uniform and continuing dependence upon the mid-century innovation model suggests that the old model has significant benefits. Like other types of public infrastructure, centralized state deployment has allowed nations to coordinate private firms, regulators, public agencies, and utilities toward the provision of an important public good: cheap, abundant energy. Where that effort was embarked upon as a major geopolitical priority, as in France and Sweden, it resulted in the fastest clean energy technology scale-up in history.[1] And yet, this deployment model is unlikely to be sufficient to re-energize the nuclear industry today for a number of reasons.

To repeat the successes of the mid-century, Western countries would have to reverse several major trends of the last few decades. R&D budgets, both public and private, have shrunk dramatically in the OECD, particularly in the United States and Western Europe—see Figure 2.[31] What R&D budgets remain are focused on basic research at the expense of development, demonstration, and deployment. In addition, the growth in demand for electricity has stagnated in Western countries since the 1980s, removing one of the main motivators to build large-scale, baseload power projects.

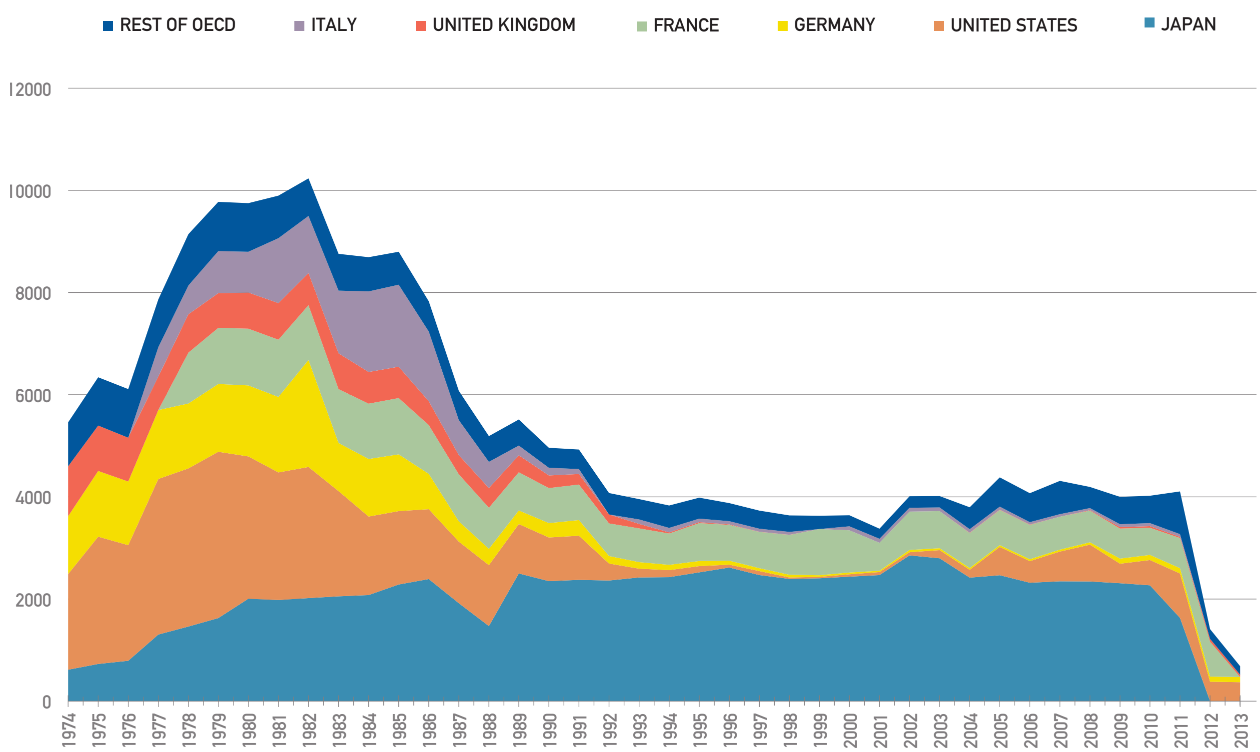


FIGURE 2. Total R&D spending on nuclear fission in OECD countries (million 2013 USD). Data from the OECD Stat Library.

US nuclear R&D funding gradually decreased at the discretion of successive presidential administrations or AEC chairs from 1963 to 1975.[40] In Figure 2, the fission R&D funding for OECD countries shows a spike in spending in the 1980s and then a sharp decline.[31] More recently, R&D spending in France and Japan has declined 30% and 50%, respectively, since 2000.[31] In Japan, advanced reactor and fuel recycling projects have suffered many problems, delays, and setbacks. In France, recent issues with the EPR at Flamanville have similarly curbed enthusiasm for new innovation in nuclear design. More generally, as industrial policy has fallen out of fashion and governments have turned toward austerity, Western governments have lost their appetite for costly advanced demonstration projects.

Nuclear innovation, as measured by patent data, is driven both by R&D investment and demand-pull, as measured through ongoing nuclear power builds.[41] Unfortunately, that means that innovation has been further hindered by stalled deployment of new reactors in Western countries. After the Three Mile Island accident, both construction times and costs skyrocketed, and the United States stopped building new reactors for roughly 30 years.[42] Despite the relative success of nuclear in France, its authorities are increasingly favoring renewables over nuclear.[1] The Fukushima Daiichi accident in 2011 deeply eroded support for nuclear energy in general and the traditionally close relationship between regulator and the nuclear industry in Japan more specifically.

The deregulation of power utilities has further challenged the state-led nuclear development model, eliminating centralized planning of regional electric grids, with much of the decision-making on what type of plant to build left to individual utilities or independent power vendors. In a deregulated market, nuclear, with its high upfront costs, long construction times, and negative public image, is unlikely to be a utility's first choice. Even with national targets to reduce CO_2 emissions, there is no reason that a utility in a deregulated market would take the risk to build a nuclear plant, especially in the United States, where natural gas prices (and power plant costs) are at historic lows. In the United States, emissions reductions mandated by the Clean Power Plan can be met entirely with natural gas and renewables. Even in regions where capacity markets are starting to take effect, the timescales are too short and uncertain for long-term planning for new nuclear projects.

For these reasons, revitalizing the traditional nuclear innovation model in the United States and Europe would require reversing robust political and economic trends in both the public and private sectors. But even were such a reversal feasible, a return to the mid-20th-century nuclear innovation regime might not be desirable.

While nuclear power has unquestionably improved over time, most of the innovation has been incremental. In the United States, innovations in operations and management have improved the performance at existing plants such that the equivalent of 17 GW of capacity was added since the 1990s.[2] Advanced fuels designed for existing reactors could increase power output and improve safety even further. New light-water designs include some passive safety features and have much lower probabilities for accidents. Construction of the AP1000 includes some modular fabrication techniques, and fully modular, small light-water reactor designs could play an important role in the short-term. But none of these advances are truly disruptive to the nuclear industry, nor are they likely to change nuclear economics, especially in competitive power markets.

Moreover, a sector that evolved to develop and deploy light-water reactors appears poorly suited to the sort of innovation that would be necessary to develop very different nuclear technologies better suited to present-day circumstances. State-controlled nuclear developers in many cases have succeeded in standardizing reactor designs quickly, but at the cost of down-selecting or restricting their technological development too early, without planning for the long-term needs of nuclear power: sustainable fuel cycle, load following, industrial process heat, distributed generation, and waste disposal.

Once state-sponsored nuclear incumbents settle on a design, incentives for further innovation change. Whether in the United States and France in the 1960s or South Korea and China more recently, national interest motivated the initial development of domestic reactors and supply chains. Developing national capabilities for nuclear power was considered a strategic necessity. In most of the countries reviewed above, nuclear provides a significant proportion of electricity generation. Therefore, relying exclusively on foreign expertise for nuclear technologies was never going to be the preferred option, especially for countries with strong central governments and an energy-intensive economy—hence the consistent focus of nations to indigenize nuclear designs, capabilities, and supply chains. But once those national capabilities are developed, there is little incentive to radically overhaul existing designs.

Even in those countries actively pursuing nuclear today, efforts to develop truly radical new designs have so far only achieved limited success. Determined to operate 150 GW of nuclear power by 2030,[22] China has greatly increased its R&D expenditure and has shifted some of its research emphasis to advanced reactors.[43] In recent years, China has made large investments in two advanced reactor projects: molten-salt and high-temperature gas reactors. They've also built a Russian-designed sodium-cooled fast reactor, and had plans to import an additional two large BN-800 SFRs (but these plans are now on hold). South Korea is currently working on a liquid-metal breeder reactor and high-temperature hydrogen generation capabilities. But its low R&D spending suggests that it is only partially committed to developing these new designs. India, another nation that has often spoken of its plans to invest in developing thorium-based reactors and fuel recycling capabilities, has also seen serial delays in those efforts.[44]

Similar perverse incentives plague firms that build and operate nuclear plants. If there are only a few credible nuclear developers, such that governments and utilities have little choice but to use them, then innovating is no longer a commercial necessity (in the few countries with more than one nuclear developer, the situation is only marginally better). Commercial discipline is often lacking, meaning that projects can go over budget with impunity, and many projects are "gold-plated" as utilities are allowed to pass costs of any capital expenditure to ratepayers.[45]

As an example of the problem with technological lock-in and lack of competition, we can look at Areva's European Pressurized Reactor (EPR), currently under construction in France, Finland, and China. The EPR is the largest nuclear reactor core ever built at 1.65 GWe and has multiply redundant active and passive systems. It was originally designed to be a cheaper option, taking advantage of economies of scale. However, the reactor pressure vessel is so large that it can only be fabricated at a small number of facilities around the world. The reactor also uses 25% more steel and 75% more concrete on a per-MW basis compared to the PWRs we have operating today.[46]

While Areva spent billions designing and licensing its new reactor, the demand will likely be limited to a half-dozen orders, as it doesn't meet European market needs. Four are currently under construction, with another two planned for the United Kingdom. The rising anticipated costs of the UK EPR at Hinkley C have been widely criticized. But despite significant delays and costs approaching triple the original estimates for projects in Finland and France, the United Kingdom has persevered with the Hinkley C project, in no small part because the EPR is the only reactor licensed in the United Kingdom at this time.[47] The lack of competition means that many European countries are stuck with the EPR or no nuclear at all.

TOWARD A 21ST-CENTURY MODEL OF NUCLEAR INNOVATION

To foster the development of a new generation of nuclear technology capable of meeting present-day environmental and economic needs, the nuclear innovation system will need to shift toward a more competitive and nimble model. This presents an opportunity for the United States. Diverse and liberalized power markets, rising costs associated with public works projects, and changing attitudes about the role of government in industrial development have bedeviled the incumbent nuclear industry. But those same challenges might become assets for a new advanced nuclear sector led by smaller players and outsiders better suited to the kind of technological disruption that the sector needs today.

The highly competitive, liberalized electricity market is already encouraging a number of nuclear start-ups to attempt to disrupt the market with more radical designs.[48] And America's world-class nuclear engineering programs and network of national labs are valuable assets for burgeoning innovators, as is its well-developed venture capital and entrepreneurial sector. Changing trends in national innovation systems suggest that a networked, bottom-up, privately led nuclear innovation effort might succeed where the old top-down innovation model has failed.

That should not be read as a call to dismantle the public institutions that have played a critical role in the development of nuclear energy as a clean and cheap source of electricity that still accounts for almost 20% of US generation. But to assure a future for nuclear energy in the United States and beyond, those institutions, including the Nuclear Regulatory Commission, the Department of Energy, and the National Laboratories, will need to change, expanding their missions to support private-sector innovation and facilitate commercialization of innovative nuclear designs.

LESSONS FROM OTHER INDUSTRIES

The nuclear industry is not the first advanced technology sector that has had to transform itself in the face of new social, economic, and political challenges. In the case studies that follow, we consider four similar industries that have better records of successful innovation: wide-body aircraft, pharmaceuticals, commercial spaceflight, and unconventional gas extraction. We consider the structure of those sectors, the networked relationships between public and private actors that characterize innovation within them, and the public policies and institutions that have allowed them to successfully innovate.

WIDE-BODY AIRCRAFT

The aviation industry bears a striking resemblance to the nuclear sector. New designs in both industries require large investments and can take decades of R&D. Deployment is dominated by large, incumbent manufacturing firms, who have or formerly had state ownership or significant support.[49] But unlike the nuclear industry, it has also delivered radical innovation on a semi-regular basis. And while some of these new designs have been more successful than others (Boeing's Dreamliner versus Airbus's A380), few would contest the marked superiority of current jets over those of the past.

If there are multiple factors that played a part in the success of the aviation industry, two are of particular relevance to nuclear. First, recent innovative efforts from airplane manufacturers have moved away from economies of scale to economies of multiples.[50] Indeed, the relative failure of enormous jumbo jets such as the Airbus A380 highlights the trade-offs between economies of scale and the flexibility of smaller designs. It is only once they start producing hundreds of units that Boeing and Airbus really see their production costs fall, and the smaller the designs, the quicker those economies come into play. Medium-sized jetliners also appeal to a larger diversity of airlines, giving more flexibility to add and change routes, whereas large wide-body aircraft are only appropriate for the most popular routes.[51]

The other, and probably most important, factor driving the industry's innovative success is an almost guaranteed demand for both existing and new designs. In particular, standing orders allow Boeing and Airbus the confidence to invest in large-scale innovation efforts for new aircraft designs, upward of $25 billion for a new design.[52] Compared with a $500 million estimated cost to develop a new nuclear design,[35] Boeing takes a much larger risk on its investment than the nuclear industry. This stable demand is what allows it to make investments that won't pay back for many years. However, even with this large demand, both Boeing and Airbus are reported to frequently sell aircraft at a loss, and stay afloat with public subsidies.[53] Boeing benefits from large defense contracts, and Airbus is heavily supported through low-interest loans (and long-delayed payback) from the European Union.[53]

Of course, one of the reasons both firms can be confident they will sell their designs is that the industry is essentially a duopoly between Airbus and Boeing, with each company controlling roughly 40% of the wide-body aircraft market. But consolidation was only possible in the aviation industry as a result of rapid growth in demand for air travel and the intense competition introduced among airlines after they were deregulated.

Commercial aviation has also benefited from the substantial role that government has played as a demanding consumer of nascent aviation technologies. From early contracts with the US Postal Service[53] to the enormous investments in airplane manufacturing during World War II to post-war military development of jet turbines, public procurement of aviation technologies, mostly for military purposes, has created initial markets for radical innovations in aviation technology. While not necessarily at the same scale, public procurement of advanced nuclear for national laboratories, military bases, or public universities and hospitals could play a similar role for advanced nuclear innovation, as could the inclusion of nuclear in state- and country-level clean energy mandates.[54]

PHARMACEUTICALS

The development of new pharmaceutical drugs may seem completely opposite to building large power plants, but its innovation process is similarly long and expensive.[55] Furthermore, the predominant innovation model, whereby smaller and larger firms combine to develop new drugs, is often cited as the ideal of today's nuclear entrepreneurs.

The pharmaceutical industry is composed of a diverse mix of firms; small biotech firms tend to specialize in the early development of new drugs while larger pharmaceutical firms focus on commercializing them. Interestingly, this existing model was not prevalent until relatively recently.[56] For much of the late 20th century (and certainly until the early 1990s), most drug development was the remit of a small number of large firms,[57] not unlike today's nuclear industry.

Part of the reason for this shift in industry structure lies in the fact that smaller and newer biotech firms were more successful at applying novel research methods such as genetic research and computer modeling.[58] They simply possessed the superior expertise. And it is quite possible that the same computing technology that revolutionized pharmaceuticals could also change the face of nuclear R&D. More generally, the current wave of nuclear start-ups suggests these newcomers believe they have some sort of comparative advantage over the large incumbents. But even if these newcomers are better able to harness new techniques, it is unlikely they will be able to develop, fund, and build new reactors entirely on their own. As they get closer to the latter stages of development, they will need the support of bigger players, exactly as biotech start-ups have.[59] With over 40 advanced nuclear start-ups in the United States, one might expect the large nuclear firms to play a similar role, although the importance of intellectual property is significantly lower with nuclear technologies. However, the success of the small modular nuclear developer NuScale appears to follow this model. NuScale started as a university spin-off in 2007, and in 2011 the global engineering and construction company Fluor became the primary investor. Rolls Royce has also become an investor, hoping to assist in the factory production of its technology.[60]

Of course, the mere existence of nuclear start-ups is hardly enough to guarantee that the pharmaceutical model will be adopted. But based on the history of that industry, two factors are likely to play an important role: (a) a successful test case and (b) regulatory reform. In the pharmaceutical example, larger firms were initially reluctant to collaborate or acquire smaller firms, and it was only after early successes such as Genentech's collaboration with Eli Lilly and Kabi that inter-firm collaboration became the norm.[57] Just as the pharmaceutical industry needed a few successful examples, so will the nuclear industry.

The other key aspect of the pharmaceutical innovation system is its regulatory framework. In recognition of the tremendous costs associated with developing new drugs, the Food and Drug Administration created a staged licensing process, whereby different pre-commercialization innovation successes (e.g., drug effectiveness in small trials) get formal regulatory validation. This system has allowed start-ups to get funding, perform trials, and complete discrete steps in the licensing process with confidence that the chance of an acquisition (and a large payout) is high, even as their drug is still years away from commercialization.[61] Replacing the Nuclear Regulatory Commission's current opaque system with a more transparent one is critical to any effort to foster greater collaboration between start-ups and traditional players.[62]

COMMERCIAL SPACEFLIGHT

Commercial spaceflight is another industry that, from an innovation standpoint, has much in common with the nuclear industry. Before 2011, the United States was a minor player in commercial space launches, with no launches in 2011. But by 2014, the United States had more launches per year than Europe and Russia combined (previously the two dominant players).[63] This was due to a very recent shift in government policy where NASA chose to halt development of a new launch vehicle to replace the Space Shuttle and rely on private launch services for both cargo and crew.[63] Before this shift, delivering human cargo into space was assumed to be the sole domain of federal space agencies, although they contracted with private vendors, and new launch designs came from decadal public development programs costing billions of dollars. Much as is the case for nuclear, the appetite for large-scale, state-led development is gone in the United States. Understanding how that shift was managed may therefore be instructive.

Although NASA's charter was changed in 1984 to encourage commercial spaceflight, it was not until 2005 when NASA allocated $500 million for commercial development under the Commercial Orbital Transportation Services program that the old model of spacecraft development was upended. The policy innovation was to ditch the old model of government procurement and contracts in favor of more flexible Space Act Agreements.[64] NASA put the entire development process in the hands of private companies, rather than contract firms to develop rockets to meet NASA's specific needs with cost-plus deals.[65] Additionally, NASA suspected small and newer firms would be more innovative and able to deliver significantly cheaper launch services than the large, incumbent aerospace firms.[64] One of the most important aspects of these programs was that NASA didn't down-select technologies; they awarded funding to any company that met a predetermined set of criteria. NASA was also explicitly trying to develop a robust commercial spaceflight industry, not solely to find a single company to deliver cargo. So as an alternative approach, starting in 2006, NASA also awarded unfunded Space Act Agreements, which gave companies advice and consulting on their technology from experienced NASA engineers and also allowed them access to NASA facilities.[64]

Through this effort, they encouraged collaboration between companies to identify shared challenges, such as educating the investment and insurance communities and developing a customer base for non-NASA orbital transportation services.[66] They also helped match companies with vendors, and stimulated entrepreneurship along the supply chain, by hosting events that brought applicants and suppliers together under one roof.[66] NASA's status as a disinterested third party played a key role in allowing different companies to come together. In sum, NASA has been able to stimulate intense private-sector activity through a combination of Space Act Agreements and network building (both between public and private and between private and private). At least a priori, there is no reason why today's nuclear-focused public institutions couldn't do the same.

The commercial space industry also benefited from favorable regulation, particularly a moratorium on regulation of the safety of crew and passengers for its first ten years (later extended to twenty years).[63] The federal government also provides indemnification against catastrophic accidents that exceed private insurance, up to $500 million per launch. Both of these policies were justified because commercial spaceflight is a young industry and was thought to be uncompetitive with Russian, European, and Chinese firms that are heavily state-supported.[63]

In 2012, SpaceX delivered its first cargo to the International Space Station, just 10 years after the company was founded.[65] In 2014, the US commercial spaceflight industry had $1.1billion in revenues.[63]

UNCONVENTIONAL GAS EXPLORATION

In the United States, the most significant energy technology breakthrough in the last few decades has been the development of hydraulic fracturing. This revolutionary technique has brought previously uneconomic gas and oil resources into play, reshaping the energy market in the United States and internationally. But the shale revolution hardly happened overnight, and for much of the late 20th century, the expert consensus was that, while shale exploration was possible, it would never be economically competitive. This is also the view of many observers of the nuclear industry, so understanding how its success came about is instructive to nuclear advocates.

Like most of the technologies looked at above, the success of hydraulic fracturing is the story of closely collaborating public and private organizations.[67] Hydraulic fracturing, in its successful form, was the result of multiple smaller technological advances, relating to underground mapping, microseismic imaging, the composition of hydraulic fracturing fluid, and even innovative drill bits.[68] And as in each of the cases, the government both provided public funding for experimenting with new materials and techniques and fostered inter-firm collaboration as well as knowledge transfer between industry and the national labs.[69]

On the surface, these interventions are hardly unique to the shale gas case, and yet certain aspects of how they were implemented deserve to be highlighted. While the government provided joint funding for demonstration projects, the actual decision for what those projects should do often rested with a consortium of industry players.[70] In other words, industry was able to make use of the significant resources of public institutions (and more than funding, it was often their expertise that was most coveted) to solve the particular problems they faced.[71]

The government also played a unique role in creating an industry consortium called the Gas Research Institute.[72] Funded through a federally approved levy on interstate pipelines, the group was tasked with developing critical technological capabilities for the industry and played a major role in developing key components of hydraulic fracturing. In exchange for approving the levy, the government would review and approve GRI's research priorities every five years (to ensure that they had a wider public benefit) and requested that much of their research results be made freely accessible.[72] Just as NASA did in the commercial spaceflight industry, the government was able to use its unique position to foster and drive inter-firm collaboration. Given that most of the firms working on unconventional gas were small, these institutions were essential to their success. The parallels to today's blossoming nuclear start-ups are clear.[73]

Of all the possible policy changes suggested by this review, encouraging the state to create more active institutions for inter-firm collaboration is probably one of the lowest hanging fruits. Not only are the costs low, but the pre-existing network of nuclear-focused national labs is also the perfect platform on which to foster these kinds of institutions. In the case of shale gas, the national labs were a critical cog of the network of players focused on hydraulic fracturing, collaborating with both individual firms and GRI. Attempting to replicate that success can only help boost nuclear innovation.

KEY RECOMMENDATIONS TO MODERNIZE THE US NUCLEAR INNOVATION SYSTEM

With its world-leading universities and national laboratories, decades of experimental experience with novel nuclear designs, start-up culture, and unique venture capital sector, the United States boasts advantages that, if well marshaled, could bring disruptive, game-changing nuclear energy technologies to market. But taking full advantage of these assets will require far-reaching changes. Successful development and commercialization of radically different nuclear energy technologies will require a radical reorganization of the nuclear sector.

Licensing of new nuclear technologies will need to be reformed in order to support smaller, more entrepreneurial start-ups as they wend their way through the licensing process and build investor confidence as key technical and licensing benchmarks are achieved.[62] National laboratories will need to make technical resources, expertise, and equipment available to private firms developing innovative new nuclear technologies. Public R&D should be targeted to solve shared technical challenges faced by advanced nuclear technologies, such as advanced materials, novel fuels, or regulation. Policy and funding should be designed to encourage inter-firm collaboration and knowledge spillovers. Public investments to demonstrate and commercialize advanced nuclear design should follow private investment, not lead it, and avoid early down-selection of single favored technologies. Like commercial spaceflight, the nuclear industry should have many innovative firms competing for contracts in parallel. While these changes, individually and in sum, would be far-reaching, the case studies summarized above demonstrate that they are not without precedent.

LICENSING AND REGULATION

The transformation of the biotech industry in recent decades has been a shift not unlike that which the nuclear sector will need to undergo. That shift has been aided by the Food and Drug Administration as well as a number of other policies to increase private R&D. Unlike the FDA and Federal Aviation Administration, the Nuclear Regulatory Commission is unique in not having a dual mission to both assure the safety of the technologies it regulates and promote the broad diffusion of those technologies for the public good.[62] If the federal government is serious about developing advanced nuclear technologies, it will need to explicitly change the NRC's mandate to a dual one, or create an agency that more explicitly promotes innovation and commercialization of new nuclear designs.

The NRC was structured when established nuclear firms were primarily in the business of building well-known designs. For a more innovative and dynamic system, regulation needs to follow a staged process similar to that of the FDA, where designs are evaluated earlier and more often in the development process, allowing companies and investors to adjust and evolve their designs. The NRC will also need to shorten the review process and create a fast track for certain designs, as the FDA does. More importantly, the funding model for the NRC needs to change, making it easier for smaller firms to license their designs. The NRC currently relies on user fees for 90% of its budget, whereas that figure is only 50% for the FDA.

RESEARCH AND NATIONAL LABORATORIES

Although not enough on its own, significant and sustained research funding is essential to a healthy innovation system. Like NASA, the Department of Energy will need to shift its mission to explicitly support private-sector innovation. Following the shale gas revolution, federal research and demonstration priorities should take explicit guidance from the nascent advanced nuclear industry in exchange for clear requirements for inter-firm collaboration and publication of results and technical data from publicly funded research and demonstration projects. Giving private companies access to national lab facilities or designated test beds could also lower the costs associated with testing necessary for licensing, and allow more transparency with the regulator. This process is beginning with DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, which aims to provide national lab capability to innovators when needed, but the federal system has yet to put forward a structured system that enables innovative ideas to move from early innovation through deployment.

R&D funding also doesn't necessarily have to come from the public sector. Pharmaceuticals benefited from federal policies that explicitly pushed R&D into the private sector, including the Orphan Drug Act, Bayh-Dole, SBIR, and Stevenson-Wydler.[74,75] Similar programs could facilitate tech transfer from national laboratories and universities to private companies, but they would need support in navigating the special security concerns around nuclear materials.

DOE should identify explicit innovation targets, as NASA has done, and provide staged public support to companies that can demonstrate viable technologies to meet them. This approach should apply to both the supply chain, whether it is forging advanced steels, developing novel fuel manufacturing capabilities, or funding and purchasing services from prototypes and demonstrations. Establishing key performance criteria with timelines for decision-making and predicating public funding upon meeting those criteria can incentivize multiple firms to take multiple approaches to solve technical challenges and experiment with novel assemblages of fuels, coolants, and materials, and leverage private-sector funding for applied research and development.

COMMERCIALIZATION

Ultimately, there is little evidence that advanced nuclear designs will get to market without some public cost sharing or market support.[76] How that is done, however, could critically shape the viability of the sector. Experience with both aviation and commercial spaceflight suggests that competitions, advance market commitments, and well-designed and targeted government procurement can support both the commercialization of game-changing technologies and the development of an entire industry. Currently, the first-mover disadvantages are too great, where companies shoulder the risk of regulatory decisions that can make or break a new technology.

For nuclear, this could be accomplished through an industry consortium—made up of both nuclear vendors and industrial or commercial energy customers—that both fund R&D efforts and agree in advance to purchase the result. Direct government procurement might offer contracts with national laboratories or military bases for a private company to provide electricity from a demonstration reactor. In both aviation and spaceflight, private firms invested heavily in RD&D in hopes of garnering future orders or contracts and increased investment further when initial contracts were obtained. There is no reason that a well-designed commercialization strategy for advanced nuclear could not achieve similar results in the nuclear sector, effectively structuring public finance commitments to leverage private investment in research, development, and demonstration of advanced nuclear technology.

Nuclear's two significant benefits over other energy sources—zero emissions and reliability—are currently not valued in most energy markets. Thus, it will also be important to develop new policies that focus on demand-pull for new nuclear production. Beyond the direct procurements and advance market commitments outlined above, market reforms and incentives may also help. Shale gas benefited from a 30-year production tax credit for unconventional gas. Under the Orphan Drug Act, the FDA fast-tracked and subsidized new drugs for rare diseases. For nuclear, a production or investment tax credit could help first-of-a-kind advanced reactors, but other market reforms such as capacity payments, clean energy standards with tradable credits, or a carbon tax may provide long-term demand support.

Finally, the recently announced Mission Innovation and Breakthrough Energy Coalition efforts offer significant potential for advanced nuclear innovation, in the United States and beyond. With Mission Innovation, over 20 countries and the European Union have committed to double federal R&D funding for clean energy technologies, encouraging collaboration among these countries. The Breakthrough Energy Coalition brings together a broad group of private investors to fund early-stage R&D in potentially disruptive clean energy technologies. But it is worth considering whether the current model, with the public Mission Innovation effort in the lead, and the private Breakthrough Energy Coalition effort following on with additional resources, ought to be inverted. The new philanthro-capital sector represented by the Breakthrough Energy Coalition has resources that rival those of most governments, including technology leaders across a range of industries.

In cutting-edge technology sectors, governments often underwrite the innovation infrastructure—basic science, research laboratories, a regulatory framework, targeted support to solve technical challenges, and tax and other incentives to support private-sector research and commercialization.[77] But it is the private firms who are able to develop disruptive innovations that meet market demands, and direct and discipline investment to commercialize those technologies. With the right policy environment, it is worth considering whether the Breakthrough Energy Coalition and its partners should lead on advanced nuclear innovation, with the US Mission Innovation initiative facilitating that effort with support for basic research, demonstrations of key technical capabilities, matching funding for advanced reactor designs that have achieved key performance benchmarks and have significant private investment lined up, and advance market commitments to support commercialization of promising designs. This arrangement, to some degree, is not that dissimilar to the role that the Gas Research Institute and its industry leadership played in supporting the shale gas revolution.

Unlike aviation, commercial nuclear power doesn't have a hungry market, although we hope there would be with the urgency of local air pollution and global climate change. However, there exist a suite of policies available for the government to stimulate market demand for nuclear power, which could position the United States as a world leader for nuclear power exports globally. Federal production or investment tax credits are a good way to limit the financial risk from uncertain power markets for new nuclear projects. Similarly, loan guarantees can ease the cost of financing. Federal or state government could also sign Power Purchase Agreements with new or existing nuclear projects. To stimulate demand, states could implement Low-Carbon Portfolio Standards in place of current Renewable Portfolio Standards.

Taken together, such a shift would represent a sea change in nuclear innovation policy, one unprecedented in the nuclear sector anywhere in the world. But doing so, we believe, represents the most likely path to the development of advanced nuclear reactors capable of competing with fossil fuels without either ongoing subsidies or centralized, state-mandated deployment. It would also align the nuclear sector with the best innovation practices of the 21st-century economy.

BIBLIOGRAPHY

1. Cao, J. *et al.* China-U.S. cooperation to advance nuclear power. *Science (80-.).* **353,** 547–548 (2016).
2. Lovering, J. R., Yip, A. & Nordhaus, T. Historical construction costs of global nuclear power reactors. *Energy Policy* **91,** 371–382 (2016).
3. BP. BP Statistical Review of World Energy. (2016).
4. IIASA. Primary, Final and Useful Energy Database (PFUDB).
5. Lovering, J. Another Record Year for Nuclear Power. *The Breakthrough Institute* (2017).
6. Rogner, H. Nuclear power and climate change. *Department of Nuclear Energy, International Atomic Energy Agency. Vienna, Austria* **II,** 1–11 (2002).
7. BP. *BP Statistical Review of World Energy*. (2014).
8. Nian, V. & Chou, S. K. The state of nuclear power two years after Fukushima - The ASEAN perspective. *Appl. Energy* **136,** 838–848 (2014).
9. Institute for Energy Research. As U.S. Shutters Coal Plants, China and Japan are Building Them. (2015). Available at: http://instituteforenergyresearch.org/analysis/as-u-s-shutters-coal-plants-china-and-japan-are-building-them/?pfstyle=wp.
10. OECD. Nuclear New Build: Insights into Financing and Project Management. *Nucl. Dev.* (2015).
11. Rong, F. & Victor, D. *What Does it Cost to Build a Power Plant?* (2012).
12. Jewell, J. Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs. *Energy Policy* **39,** 1041–1055 (2011).
13. Deutch, J. M., Kadak, A. C., Kazimi, M. S. & Moniz, E. J. Future of nuclear power. *Update* 20 (2009).
14. Nordhaus, T., Lovering, J. & Shellenberger, M. *How to Make Nuclear Cheap*. (2013).
15. OECD Nuclear Energy Agency. Technology Roadmap Update for Generation IV Nuclear Energy Systems. 1–66 (2014).
16. MIT. *Future of nuclear power. Environment; (United States)* (2003).
17. Allen, T., Fitzpatrick, R. & Milko, J. The Advanced Nuclear Industry: 2016 Update. (2016). Available at: http://www.thirdway.org/infographic/the-advanced-nuclear-industry-2016-update.
18. Bent Flyvberg. What You Should Know About Megaprojects and Why: An Overview. (2009). doi:10.1002/pmj
19. Lester, R. A Roadmap for U.S. Nuclear Energy Innovation. *Issues Sci. Technol.* (2016).
20. Trabish, H. K. Nuclear industry darkened by delays, cost overruns at Vogtle & Summer facilities. *Utility Drive* (2015).
21. Burgis, T., Stacey, K. & Stothard, M. EDF's nuclear troubles rooted in caution. *Financial Times* (2016).
22. World Nuclear Association. Nuclear Power in China. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

23. McDonald, J. China sets sights on new global export: nuclear energy. *Phys.org* (2016).

24. VVER. *Wikipedia*

25. Hyun-cheol, K. Korea Seeks to Export 80 Nuclear Plants by 2030. *The Korea Times* (2010).

26. King, L. What Matters Most? (University College London, 2016).

27. World Nuclear Association. Government Structure and Ownership. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx.

28. Association, W. N. Nuclear Power in South Korea. *Country Profiles.* (2017).

29. Jia, H. R&D share for basic research in China dwindles. *Chemistry World* 8–10 (2014).

30. AAAS. Historical Trends in Federal R&D. Available at: https://www.aaas.org/page/historical-trends-federal-rd#Char.

31. OECD. OECD Stat Library. Available at: http://stats.oecd.org/index.aspx?r=137063.

32. Stott, D. South Korea's Global Nuclear Ambitions. *Asia–Pacific J.* 1–16 (2010).

33. Weinberg, A. M. *Nuclear Reactions: Science and Trans-Science*. (American Institute of Physics, 1992).

34. Hewlett, R. G. & Holl, J. M. *Atoms for Peace and War: 1953-1961*. (University of California Press, 1989).

35. Finan, A. E. Energy System Transformation: An Evaluation of Innovation Requirements and Policy Options. (MIT, 2012).

36. Cochran, T. B. *The Liquid Metal Fast Breeder Reactor*. (John Hopkins University Press, 1974).

37. IAEA. *Nuclear Power Reactors in the World*. (2013).

38. Escobar Rangel, L. & Lévêque, F. Revisiting the cost escalation curse of nuclear power: New lessons from the French experience. *Econ. Energy Environ. Policy* **4,** (2015).

39. World Nuclear Association. Nuclear Power in Japan.

40. Management Information Services & NEI. *60 Years of Energy Incentives*. (2011).

41. Berthélemy, M. *What drives innovation in nuclear reactors technologies? An empirical study based on patent counts*. **33,** (2012).

42. Lovering, J. R., Yip, A. & Nordhaus, T. Historical construction costs of global nuclear power reactors. *Energy Policy* **91,** 371–382 (2016).

43. OECD. China headed to overtake EU, US in science & technology spending, OECD says. (2014).

44. Ramana, M. V. A fast reactor at any cost: The perverse pursuit of breeder reactors in India. *Bulletin of Atomic Scientists* (2016).

45. Energy Policy Group. *Competition in Bilateral Wholesale Electric Markets: How Does it Work?* (2016).

46. Peterson, P. F., Zhao, H. & Petroski, R. Metal and concrete inputs for several nuclear power plants. *Univ. California, …* 1–20 (2005).

47. World Nuclear Association. Nuclear Power in the United Kingdom. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx.

48. Third Way. *Introducing the Advanced Nuclear Industry*. (2015).

49. Benkard, C. Learning and Forgetting: the Dynamics of Aircraft Production. *Am. Econ. Rev.* **90,** (1999).

50. Benkard, C. L. Learning and forgetting: The dynamics of aircraft production. *Am. Econ. Rev.* **90,** 1034–1054 (2000).

51. Curtis, T., Rhoades, D. L., Curtis, T., Rhoades, D. L. & Jr, B. P. W. *Regional Jet Aircraft Competitiveness: Challenges and Opportunities opportunities*. (2013).

52. Wu, B. Will Boeing Manage To Recoup 787 Development Costs? *AmigoBulls* Available at: http://amigobulls.com/articles/will-boeing-manage-to-recoup-787-development-costs.

53. Pandey, M. R. *How Boeing Defied the Airbus Challenge*. (2010).

54. Lovering, J., Nordhaus, T., Boisvert, W., Shaked, J. & Shellenberger, M. *Low-Carbon Portfolio Standards: Raising the Bar for Clean Energy*. (2015).

55. DiMasi, J. A., Grabowski, H. G. & Hansen, R. W. Innovation in the pharmaceutical industry: New estimates of R&D costs. *J. Health Econ.* **47,** 20–33 (2016).

56. Zucker, L. G., Darby, M. R. & Brewer, M. B. Intellectual Human Capital and the birth of US biotechnology Enterprises. *Am. Econ. Rev.* 290–306 (1998).

57. Gottinger, H. & Umali, C. Organizational Entrepreneurship: A Historical Overview on Industry Alliances in Biotech and Pharmaceuticals. *Open Bus. J.* **4,** 14–27 (2011).

58. Gambardella, A. in *Science and innovation: The US pharmaceutical industry during the 1980s* (Cambridge University Press, 1995).

59. Audretsch, D. B. The Role of Small Firms in US Biotechnology Clusters. *Small Bus. Econ.* **17,** 3–15 (2001).

60. NuScale Power. History of NuScale Power Technology. Available at: http://www.nuscalepower.com/about-us/history.

61. Lawrence, S. & Lahteenmaki, R. Public biotech 2013 — the numbers. *Nat. Biotechnol.* **32,** 1–8 (2014).

62. Nuclear Innovation Alliance. *Strategies for Advanced Reactor Licensing*. (2016).

63. GAO. *Commercial Space Launch Industry Developments Present Multiple Challenges*. (2015).

64. Young, A. *The Twenty-First Century Commercial Space Imperative*. (Springer, 2015).

65. Seedhouse, E. *SpaceX: Making Commercial Spaceflight a Reality*. (Springer, 2013).

66. Stone, D. *et al.* NASA's approach to commercial cargo and crew transportation. *Acta Astronaut.* **63,** 192–197 (2008).

67. Buck, A. *A History of the Energy Research and Development Administration*. (1982).

68. Trembath, A., Jenkins, J., Nordhaus, T. & Shellenberger, M. *Where the Shale Gas Revolution Came From: Government's Role in the Development of Hydraulic Fracturing in Shale*. (2012).

69. Burwen, J. & Flegal, J. *Unconventional Gas Exploration & Production: Case Studies on the Government's Role in Energy Technology Innovation*. (2013).

70. King, L., Nordhaus, T. & Shellenberger, M. *Lessons from the Shale Revolution*. (2015).

71. Wang, Z. & Krupnick, A. A Retrospective Review of Shale as Development in the United States. *Econ. Energy Environ. Policy* **4,** 1–14 (2014).

72. Trembath, A. Interview with William Burnett, Formerly of the Gas Research Institute: The Gas Research Institute's Evolving Role in Shale Gas. *The Breakthrough Institute* (2015).

73. Golden, J. M. & Wiseman, H. J. The Fracking Revolution: Shale Gas as a case study in innovation policy. *Emory Law J.* **64,** 995–1040 (2015).

74. Block, F. & Keller, M. R. *Where do Innovations Come From? Transformations in the U.S. Economy, 1970-2006*. (2011).

75. Love, J. & Hubbard, T. Prizes for Innovation of New Medicines and Vaccines. *Ann. Heal. L.* **1,** (2009).

76. Deutch, J. secretary of energy advisory board U.S. Department of Energy Secretary of Energy Advisory Board Report of the Task Force on the Future of Nuclear Power. (2016).

77. Jenkins, J. *et al. Where Good Technologies Come From*. (2010).

ACKNOWLEDGEMENTS

The authors would like to thank the Pritzker Innovation Fund, the Nathan Cummings Foundation, the Comer Family Foundation, and Alex C. Walker Foundation, the Anthropocene Institute, Frank Batten, William Budinger, Ross Koningstein, Ray Rothrock, John Crary, and Matthew Winkler for supporting our research.

For reviewing early drafts of this report, the authors would like to thank Per Peterson, Armond Cohen, Ashley Finan, Ross Koningstein, Jeff Navin, Ryan Fitzpatrick, Charles Forsberg, David Petti, Jacobo Buongiorno, Joseph Lassiter, John Parsonsand, and Todd Allen.

HOW TO MAKE NUCLEAR INNOVATIVE

LESSONS FROM OTHER ADVANCED INDUSTRIES

JESSICA LOVERING, LOREN KING
AND TED NORDHAUS

THE BREAKTHROUGH INSTITUTE
436 14TH STREET, SUITE 820, OAKLAND, CA 94612
510-550-8800
info@thebreakthrough.org
@theBTI

BREAKTHROUGH INSTITUTE

MARCH 2017