Mapping U.S. R&D investments needed to field a new generation of nuclear energy technologies in 2030 and beyond.

The U.S. Nuclear R&D Imperative

A Report of the American Nuclear Society Task Force on Public Investment in Nuclear Research and Development

February 2021

ANS

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Introduction

The United States has charted a path toward an unprecedented expansion of zero-carbon energy generation. Already, our energy landscape is being reshaped by a combination of technology advancements, federal and state tax and regulatory policies, and market forces. The effects can be seen in the sizable shift from coal- to natural gas-fired electricity generation, as well as the significant build-out of wind and solar generation capacity and plans to expand electric vehicle charging infrastructure.

It is becoming increasingly clear, however, that organic changes alone will not build a clean energy infrastructure at the pace and scale needed to avoid the worst impacts of global climate change. Energy systems will require the widespread availability of firm, “dispatchable” zero-carbon technologies—energy sources that can be relied upon at any time of day. The only commercially proven, zero-carbon energy technology capable of filling that role in the near term is nuclear energy. Meeting decarbonization goals as rapidly and efficiently as possible will require significant additional investments in nuclear energy research and development.

The American Nuclear Society (ANS) commissioned a *Task Force on Public Investment in Nuclear Research and Development* to bring together 20 technical experts from the U.S. Department of Energy’s national laboratories, universities, private companies, utilities, suppliers, and ANS professional divisions. This group assessed the R&D needs of the U.S. nuclear energy technology sector in the 2020s and the federal investment required to meet those needs and enable a commercial scale-up of U.S. advanced nuclear energy systems starting in 2030.

Chaired by **Dr. Christina Back**, vice president of the Nuclear Technologies and Materials Division at General Atomics, and **Dr. Mark Peters**, executive vice president for Laboratory Operations at Battelle, the Task Force undertook an aggressive six-month effort to assess current nuclear R&D funding levels, which included reviews of authorizing and appropriating legislation, agency budget justifications, and interviews with a broad cross section of the nuclear technology and policymaking community.

The report is not an exhaustive survey of all federal spending on nuclear R&D activities, nor is it a step-by-step plan for systemic overhaul. Rather, it is meant to serve as a prospectus for the nuclear policymaking community as Congress and the Administration consider options for expanding U.S. zero-carbon generating capacity, while preserving U.S. influence over global nuclear safety and nonproliferation norms and spurring economic growth through high-wage jobs in the nuclear sector.

Executive Summary

Dozens of nuclear technology companies are designing advanced reactors that will reshape how we think about nuclear power.

Backed by a recent and unprecedented surge of private investment in nuclear technologies, they recognize the market needs of a zero-carbon energy future. Some of these new reactor designs will eventually be licensed and constructed. What is not yet clear is whether they will be deployed at a scale and a pace that will rapidly impel the United States to a clean energy future.

Commercialization is not the finish line, but it will usher in a new kind of energy system—one that can be served by clean, reliable nuclear energy in a range of reactor sizes and types that share the grid with other low-carbon or carbon-free technologies. Federal investments in nuclear research and development are critical to lower costs and reduce the time to deployment, while building momentum to catalyze more private investment, more research, and more innovation. United momentum is key to deriving maximum benefit from nuclear technologies and securing America's clean energy future.

CLEAN ENERGY

Nuclear power plants operating around-the-clock generated **54.8 percent** of all carbon-free electricity in the U.S. in 2019, avoiding **505.8 million metric tons of CO_2**.

JOBS AND PROSPERITY

Nuclear energy creates high-paying jobs that last for decades. Nuclear adds **$60 billion to GDP** and provides **$12.2 billion in federal and state taxes**.

NATIONAL SECURITY

Nuclear energy contributes over **$42.4 billion annually** to U.S. national security through the added value of its workforce and supply chain infrastructure and the dependable energy it generates, according to an estimate by the Atlantic Council.

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Increased federal investment is needed now. Just as the power of compound interest rewards early investors, the benefits of increased R&D funding will accelerate future technological gains and expertise. That is why the American Nuclear Society's *Task Force on Public Investment in Nuclear Research and Development* was commissioned, and that is why the Task Force has made recommendations that look beyond the deployment of the first U.S. advanced reactors.

The nuclear imperative

Nuclear energy does more than keep the lights on. It is uniquely able to deliver climate, economic, and national security benefits.

Clean energy

Achieving bold objectives will require the broad availability of "dispatchable" zero-carbon technologies—energy sources that can be called upon at any time to meet shifting energy demand and ensure the reliability and resiliency of the U.S. power grid. Our country's clean energy infrastructure will require significant R&D investment if it is to become a reality.

Job creation

Existing nuclear power plants and the nuclear supply chain support high-paying jobs, and future nuclear technology exports will fuel greater job growth. The U.S. has surrendered its once unassailable position as the international leader in nuclear science and technologies. Through R&D investments that maintain, expand, and upgrade national nuclear testbeds, the U.S. can prepare to export technologies that the rest of the world will adopt, thereby regaining its leadership position while creating jobs here in the U.S.

National security

Ample, reliable electricity is essential to the way we live and work today, which makes energy security an issue of national security. Nuclear power can provide an independent electricity source for critical national security missions on land, and provide both power and propulsion in space and at sea.

As the U.S. increases its nuclear technology exports to burgeoning markets overseas, the nation can once again lead the world in nuclear safety, safeguards, and security. If, on the other hand, the U.S. does not regain its leadership role by building a strong nuclear enterprise, one day China and Russia may be selling reactors to us.

Climate change can literally reshape the planet we live on and threaten our national security in new ways, but nuclear energy is capable of slowing or preventing the most catastrophic effects of climate change.

Why is more investment needed?

All can agree that we need a clean energy system that is **safe, affordable, reliable, resilient,** and **secure**. Ensuring these attributes requires science, data, testing, and analysis. In short, it requires R&D.

The Task Force believes that existing nuclear R&D programs are of fundamental importance to maximize the clean energy benefits of the current fleet, ensure public health and safety, foster the technology applications of tomorrow, and provide energy security. Existing R&D programs must be sustained. But maintaining the status quo will not deliver the momentum needed now.

Recent legislation authorizing the Advanced Reactor Demonstration Program (ARDP) has provided a blueprint for federal cost-share funding for advanced reactor demonstrations. The Task Force recommends full and sustained appropriations for the ARDP to enable full-scale demonstrations by

2027 as planned. Five additional designs are supported by Risk Reduction for Future Demonstration awards, and three Advanced Reactor Concepts 2020 awards have been made. In 2028, a subset of the designs that previously received Risk Reduction awards could become candidates for the next round of demonstrations.

Decisions need data

The ARDP will use metrics and milestones to select commercial partners, similar to the approach used with great success by NASA and its partner, SpaceX. At specific milestones reactor designs must be assessed on their technological merits. Only through testing and hard data can tough choices be made. The fast-neutron Versatile Test Reactor must be constructed by 2030 to accelerate testing of advanced nuclear fuels, materials, and components. Versatility is inherent in the design of the VTR, which will support simultaneous experiments on very different reactor concepts and fill a significant gap in the country's scientific infrastructure.

If the ARDP represents a set of architect's plans—a framework for advanced reactor R&D—the people of the nuclear community must build a functional structure from those plans. Just as no building would be complete after framing, nuclear energy's future will not be secured without setting a strong foundation and building on science and data. Completing the project will require sustained funding and commitment.

SCOPE

The Task Force chose to focus on a core set of nuclear R&D programs within the Department of Energy's Office of Nuclear Energy that advance the science and applications of fission energy. While those programs also support select missions of the National Nuclear Security Administration, NASA, and the Department of Defense, the Task Force did not develop funding or programmatic recommendations for those agencies.

ANS supports the goals of fusion research led by the DOE's Office of Science. Acknowledging the recent draft report of the Fusion Energy Sciences Advisory Committee, the Task Force decided not to include fusion in the scope of its funding and programmatic recommendations.

Building an Innovation Pipeline

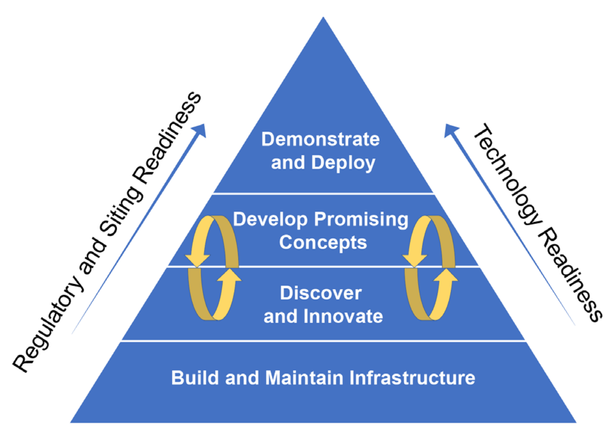
The Task Force believes it is incumbent on the DOE's Office of Nuclear Energy to ensure that the recommended investments will constitute a healthy, sustainable nuclear innovation pipeline—not just a set of loosely coordinated programs. A cohesive continuum of technology development, kept on target by assessments at key milestones, will produce reactors ready for deployment by 2030 and ensure innovations in efficiency and design for generations to come. The Task Force has identified four stages of the innovation pipeline:

Build and Maintain Infrastructure

Strengthen and expand fundamental U.S. nuclear science and technology capabilities and maintain, secure, and optimize the operations of current facilities.

Discover and Innovate

Allow the U.S. research community to propose and test numerous high-risk, high-reward ideas at universities, national laboratories, and industrial laboratories aimed at improving nuclear technology now and for generations to come.



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Develop Promising Concepts

Select and advance promising concepts at universities, national laboratories, and industrial laboratories to reduce uncertainties and to show viability.

Demonstrate and Deploy

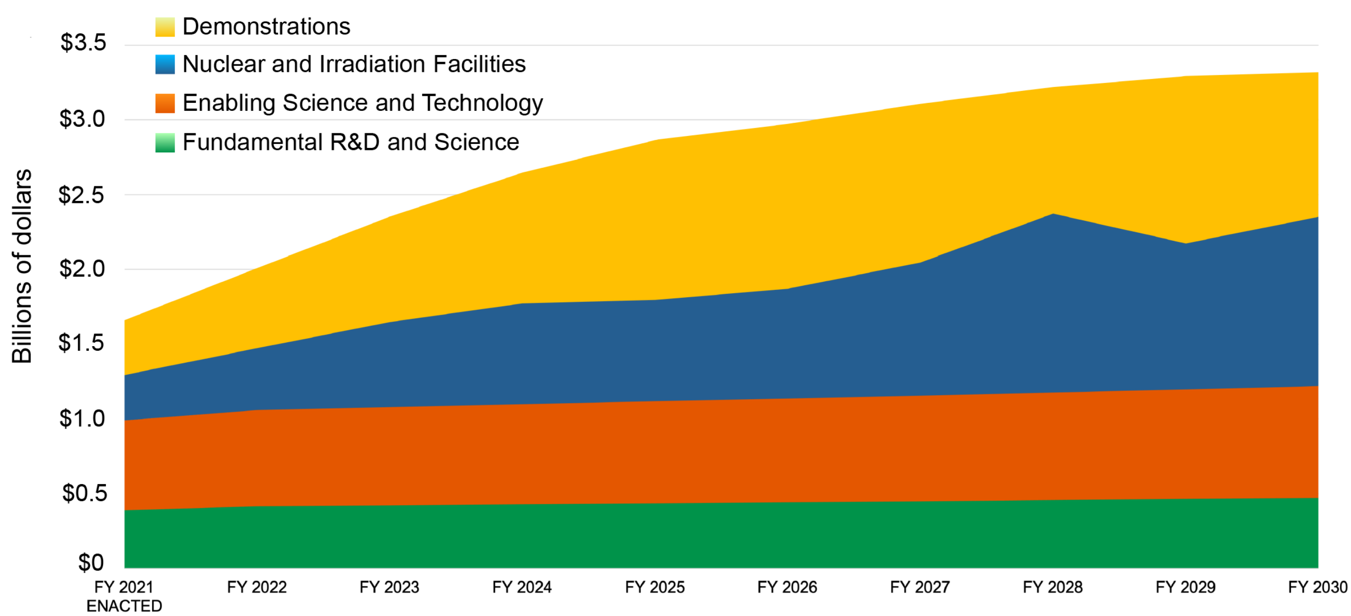
Demonstrate promising concepts to enable commercialization, often under a cost-sharing partnership with an industry-leading developer.

Every funded program, from a bench-scale university experiment to a full-scale advanced reactor demonstration, has its place in this progression. Programs must be developed apace to get maximum value from federal investments, with due consideration to every step on the pathway to deployment—from material and fuel qualification to siting and licensing. The DOE's National Reactor Innovation Center (NRIC) and Gateway for Acceleration of Innovation in Nuclear (GAIN) programs were established to connect private companies to federal nuclear R&D testbeds and must receive full federal support.

Funding recommendations

The Task Force determined that a near doubling in annual appropriated funding levels for core nuclear R&D activities would be required to be prepared to field the first of successive future generations of nuclear technologies by 2030. In all, the Task Force recommends approximately $10.3 billion in additional discretionary spending between now and 2030, when compared to levelized funding at FY 2021 enacted levels. Concepts that progress from R&D to deployment may receive early market support through other federal mechanisms.

Recommended nuclear R&D funding (FY 2021–FY 2030)



In this simplified graph of recommended funding, programs have been stacked in four categories—**Fundamental R&D and Science**, **Enabling Science and Technology**, **Nuclear and Irradiation Facilities**, and **Demonstrations**. Please refer to page 36 of this report for detailed graph of funding recommendations and for more details.

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The recommended additional federal nuclear R&D investments are a small fraction of the total cost needed to address or mitigate climate change. In comparison to the costs of President Biden's $1.7-trillion climate plan, for example, the requested additional nuclear R&D support of $10.3 billion over nine years is approximately 0.6 percent of the administration's 10-year strategy.

Building for future unknowns

The funding recommendations in this report reflect needs that the Task Force anticipates by 2030, from the vantage point of 2021. Increased federal nuclear R&D investment, coupled with the public and private research investment already underway, will yield advances in this decade. The Task Force members recognize that the future promises more than we can grasp now. Technologies that are still maturing, such as inline diagnostics and advanced manufacturing, may be used to support operational advances that we cannot foresee now. But we will learn, with time, just how our investments made today will pay off, while the world learns to recognize nuclear energy's promise of clean and reliable energy.

1 The National Imperatives for Nuclear Energy

Nuclear energy is the largest carbon-free energy source in the United States, providing reliable, dispatchable 24/7 electricity that Americans depend on today. Advanced nuclear technologies can enable cost-effective, flexible energy choices for a zero-carbon future—while strengthening national security and the economy.

A fundamental transformation in global energy systems is taking shape in all corners of the world, as policymakers and the public are increasingly demanding cost-competitive clean energy. The next generation of nuclear energy systems has the potential to play a major role in meeting that demand. Deploying new technologies domestically and being a competitive nuclear energy technology supplier internationally are both in the national interest of the United States.

While there are many compelling reasons why a thriving U.S. nuclear energy sector should be part of the nation's long-term energy strategy, three stand out above the rest: **clean energy, national security,** and **job creation.**

The clean energy imperative

The global imperative to reduce emissions of heat-trapping gases like carbon dioxide into our atmosphere was underscored by a 2018 special report—*Global Warming of 1.5 °C*—from the United Nations' Intergovernmental Panel on Climate Change (IPCC).[1] The IPCC report found that,

> "pathways limiting global warming to 1.5°C...would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems....These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options." For electricity generation, "shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modeled to increase in most 1.5°C pathways."

Transitioning global energy systems to a clean, reliable, and affordable mix requires new investments in a range of resources. This will include a significant expansion of low-carbon sources of electricity, including wind and solar generation, growth in energy storage, and a next generation of nuclear energy systems. A 2018 report from MIT titled *The Future of Nuclear Energy in a Carbon-Constrained World* modeled available technologies and concluded that nuclear energy needs to be part of the mix to achieve these goals at a reasonable cost.[2] Individual utilities have also modeled their cost of decarbonization and found that nuclear energy can reduce that cost by billions of dollars a year.[3]

A 2018 study by MIT researchers calculated that the amount of installed capacity required for a renewable- and battery-only grid would be five to eight times peak demand, as compared to 1.3 to 2.6 times peak demand when nuclear and other firm resources are available.[4] By limiting the amount of overcapacity that is required, overall costs are lowered and siting challenges decrease.

Looking specifically at the U.S., rising consumer demand for clean energy, combined with increasingly aggressive decarbonization policies of states, is driving utilities to commit to goals of deep or complete decarbonization by mid-century (see Fig. 1.1). According to the Smart Electric Power Alliance, as of December 2020 there were 61 utilities with publicly stated emissions reduction goals (36 with carbon-free or net-zero emission goals). These 61 utilities serve 68 percent of all customer accounts in the U.S.[5]

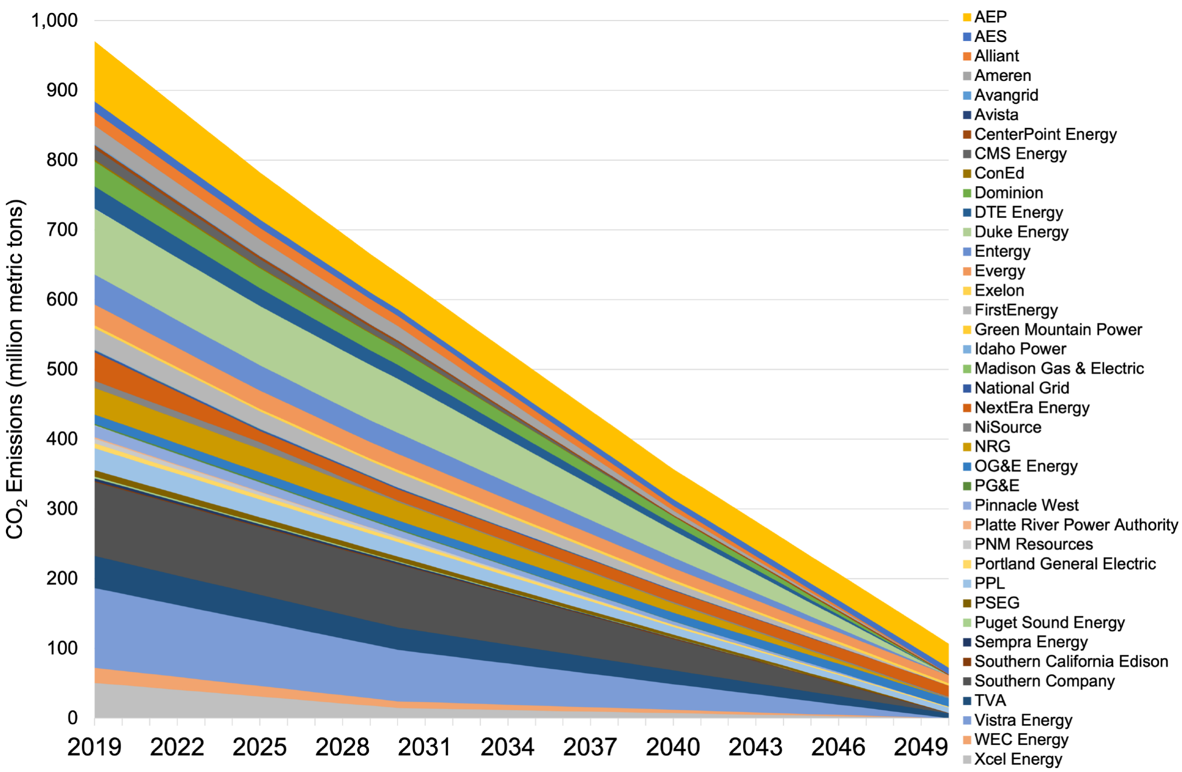

Figure 1.1. Utility carbon emission projections based on pledges. (Source: Nuclear Energy Institute)

As these utilities determine their required generating mix, they are coming to the same conclusion: To decarbonize while maintaining grid reliability and affordability, a growing share of wind, solar, and storage must be coupled with "advanced very low- and zero-carbon technologies that can be dispatched to meet energy demand."[6] Nuclear power is the only energy source that can be pragmatically scaled to fill that essential role. In 2019, the existing U.S. nuclear fleet generated 54.8 percent of all carbon-free electricity in the U.S. while avoiding 505.8 million metric tons of CO_2.[7]

Two global approaches

As nations decarbonize their energy systems, their existing energy infrastructure and anticipated demand for clean energy resources will see them follow one of two different approaches. In the established economies of the 37 countries of the Organization for Economic Co-operation and Development (OECD), energy consumption is expected to grow very slowly, on the order of 1 percent per year (see Fig. 1.2). This low anticipated growth rate, coupled with increasingly ambitious carbon reduction pledges being made by OECD nations, suggests that much of the demand for clean energy systems will be created as carbon-emitting fossil fuels are replaced by non-emitting resources like nuclear, wind, solar, and fossil fuels with CCS.

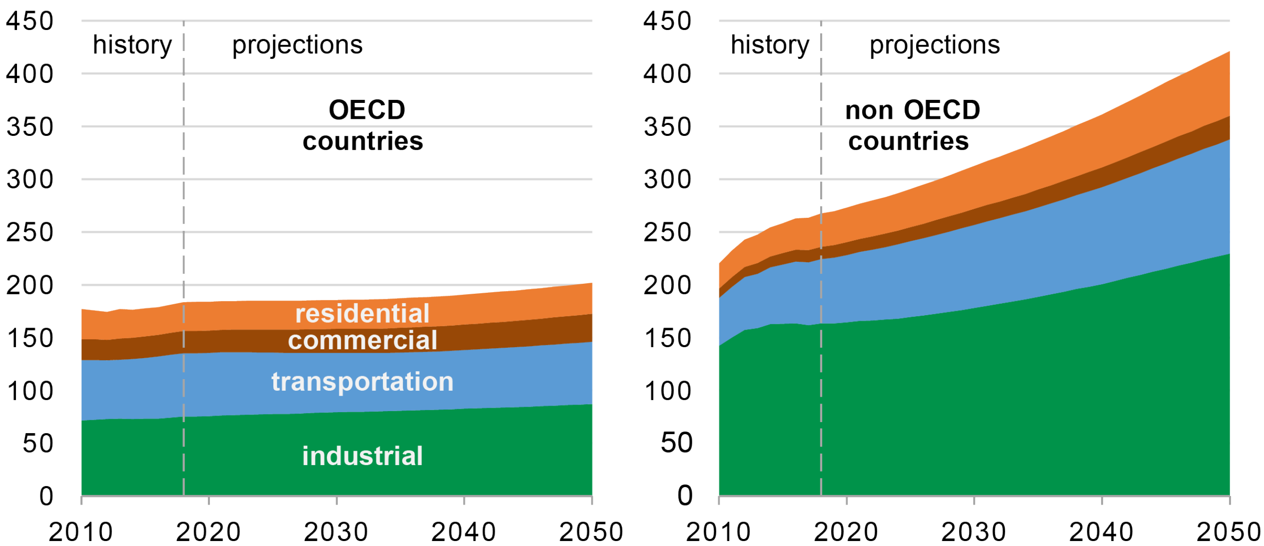

Figure 1.2. Global energy consumption by sector, 2010–2050, in quadrillion British thermal units (BTUs). (Source: U.S. Energy Information Administration, International Energy Outlook 2019 Reference case)

The situation is expected to be markedly different in the nearly 160 non-OECD countries. The U.S. Energy Information Administration expects energy use in those nations to grow by nearly 50 percent through 2050.[8] Several of the largest economies in the non-OECD nations—most notably China—have pledged to significantly reduce or eliminate carbon emissions as they increase their energy use. Tsinghua University in China published a plan for how the country might accomplish this goal, which included a nearly five-fold increase of nuclear energy use from 2025 to 2060.[9]

Unlike the OECD countries, many of these nations do not have either large-scale fossil generating facilities that need to be replaced or established electrical grids into which clean energy technologies must be incorporated. As a result, the opportunities for nuclear energy in many of these non-OECD countries look more promising than in the OECD nations. However, if the U.S. or other OECD countries move to aggressively electrify transportation systems, electricity demand could increase beyond the levels the EIA was able to project in 2019, and the market for new nuclear reactors could grow.

Beyond electricity

The scale of decarbonization called for in the IPCC report will also require an energy system transformation that reaches far beyond the electric sector. According to the U.S. Environmental Protection Agency, electricity production was responsible for only about 27 percent of U.S. greenhouse gas emissions in 2018 (see Fig. 1.3).[10]

Efforts to deeply decarbonize energy use will also have to reduce emissions from the transportation and industrial sectors, and that will require a rapid, major infrastructure build-out. According to LucidCatalyst, nuclear energy is the only energy technology that can be scaled up in a cost-competitive way to meet the anticipated staggering growth in demand for hydrogen and ammonia to decarbonize the heavy road, rail, aviation, and marine transportation sectors.[11] To meet industrial decarbonization needs, nuclear energy can directly replace fossil fuels to supply electricity in some applications, and—unlike most other sources of carbon-free generation—can also supply high-temperature process heat to decarbonize specialized industrial processes.[12]

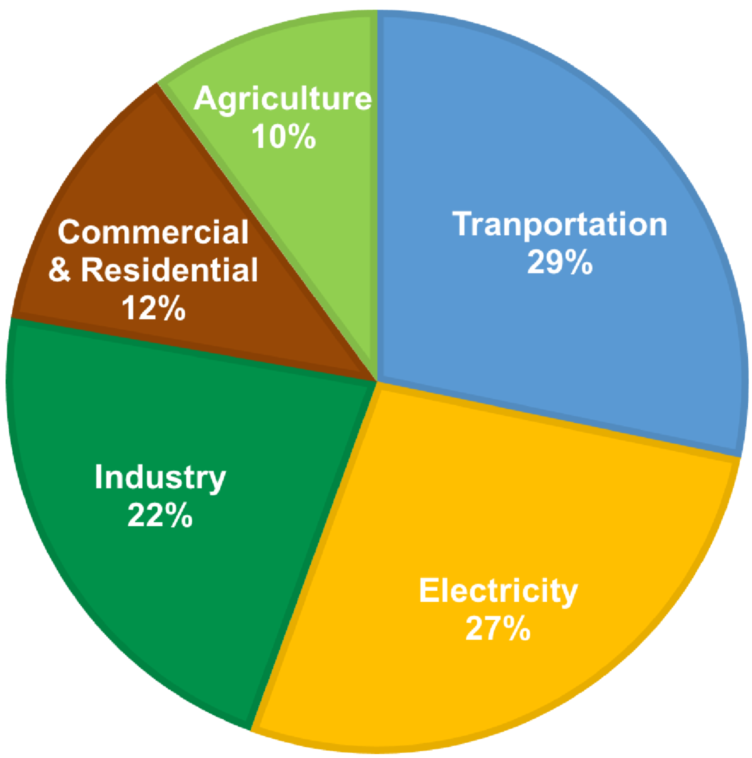

Figure 1.3. Total U.S. greenhouse gas emissions by economic sector in 2018. (Source: U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018.")

The range of market opportunities for advanced nuclear energy systems is just now being explored. The U.S. Department of Energy's cross-cutting Hydrogen Program, with participation from the Offices of Nuclear Energy, Energy Efficiency and Renewable Energy, Fossil Energy, and Science, has already made awards to four utilities to investigate hydrogen production from operating nuclear power reactors.[13] Nuclear R&D must support more than our current deployment plans to enable future carbon-free, nuclear-driven technology systems so that a clean energy infrastructure is ready when our society demands it.

The national security imperative

Because nuclear reactors can operate reliably for 80 or more years, engaging in civil nuclear trade opens the door to what can be a decades- or even century-long relationship with the recipient nation—in areas such as nuclear safety and security, physical and cybersecurity, and nonproliferation (see Figure 1.4). Beyond the role nuclear technology can play in a country's energy mix, the nuclear energy fuel cycle is related to national security and nonproliferation in a way that makes it fundamentally different from other forms of energy. These and other attributes of nuclear energy compel a long-term federal role for this technology.

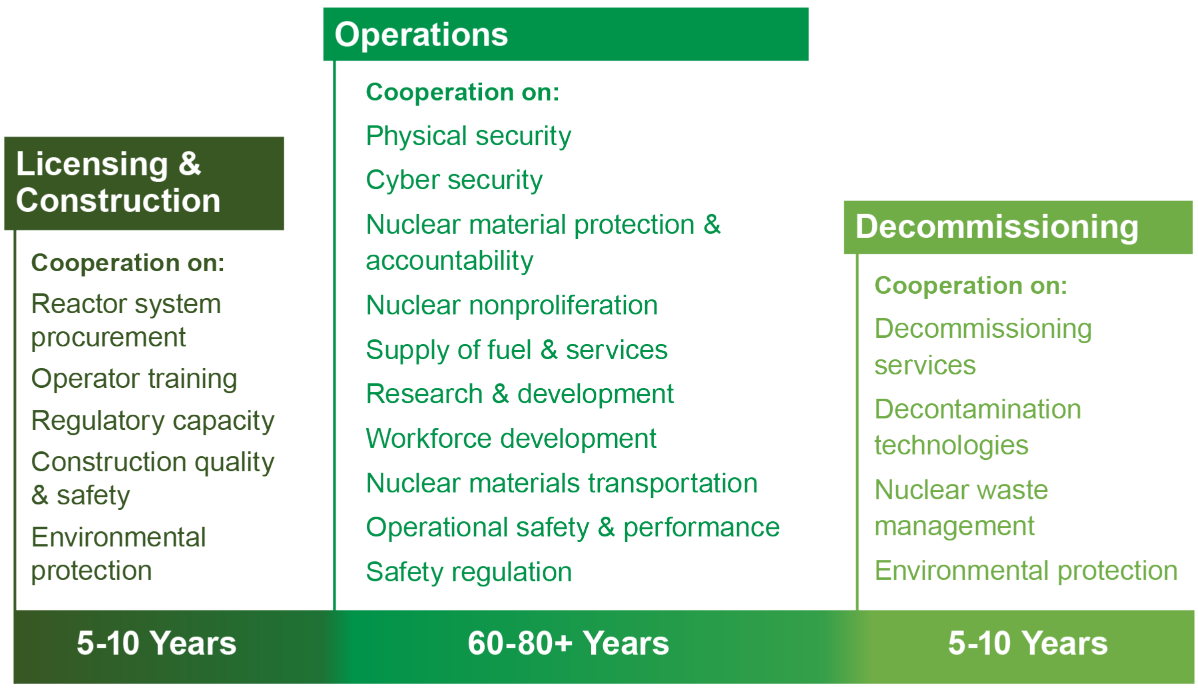

Figure 1.4. A nuclear reactor order or a contract for subsequent support can be the foundation for a century of international cooperation. (Source: NEI)

As the leading nuclear energy supplier during the first generation of global nuclear power plant construction and operation, beginning in the 1950s and continuing through the 1980s, the U.S. had a major role in setting international standards for safeguards, physical security, and safety. To ensure a similar level of influence going forward, the U.S. must remain a major player in domestic nuclear energy and a worthy competitor in international markets—offering reactor designs that incorporate security and safeguards attributes.

Despite having brought its first reactor online in the 1990s, less than 30 years ago, China is leading the world in new reactor construction, as shown in Figure 1.5. The Chinese government is funding nuclear R&D for a broad range of reactor designs.[14] Building off a strong domestic base, China is turning to exports and will have a growing influence on nuclear supplier norms.[15] As part of its $1 trillion "Belt and Road Initiative" global infrastructure development strategy, China is pursuing overseas nuclear builds in countries including Pakistan, Turkey, and even the United Kingdom. According to a former chair of the state-owned China National Nuclear Corp., China could build as many as 30 overseas reactors by 2030, earning up to $145.5 billion.[16]

Russia has exported nuclear reactors to nine different countries in the last 10 years,[17] and claims to have documented commitments to build 36 power units, with a 10-year portfolio of overseas orders exceeding $140 billion.[18] Along with robust state support from the Kremlin, Rosatom has the crucial advantage of the world's only fast neutron test reactor—the BOR-60.

In total, 29 of the 54 reactors currently under construction around the world, or 54 percent, are Chinese or Russian built.[19] Contrast this with privately-owned U.S. reactor vendors who currently have no foreign orders in a market that the U.S. Department of Commerce valued at $500-740 billion over the next 10 years.[20]

There are geopolitical and national security considerations to surrendering the nuclear energy marketplace to suppliers like China and Russia, with an attendant loss in influence over not just nonproliferation norms, but also safety and security practices.[21]

Through heavily subsidized bids, Russian and Chinese state-owned nuclear suppliers undercut commercial competitors and ensnare buyers with all-encompassing "build-own-operate" terms and government financing. This "debt-trap diplomacy" undermines both the sovereignty of the host countries and U.S. national security interests.

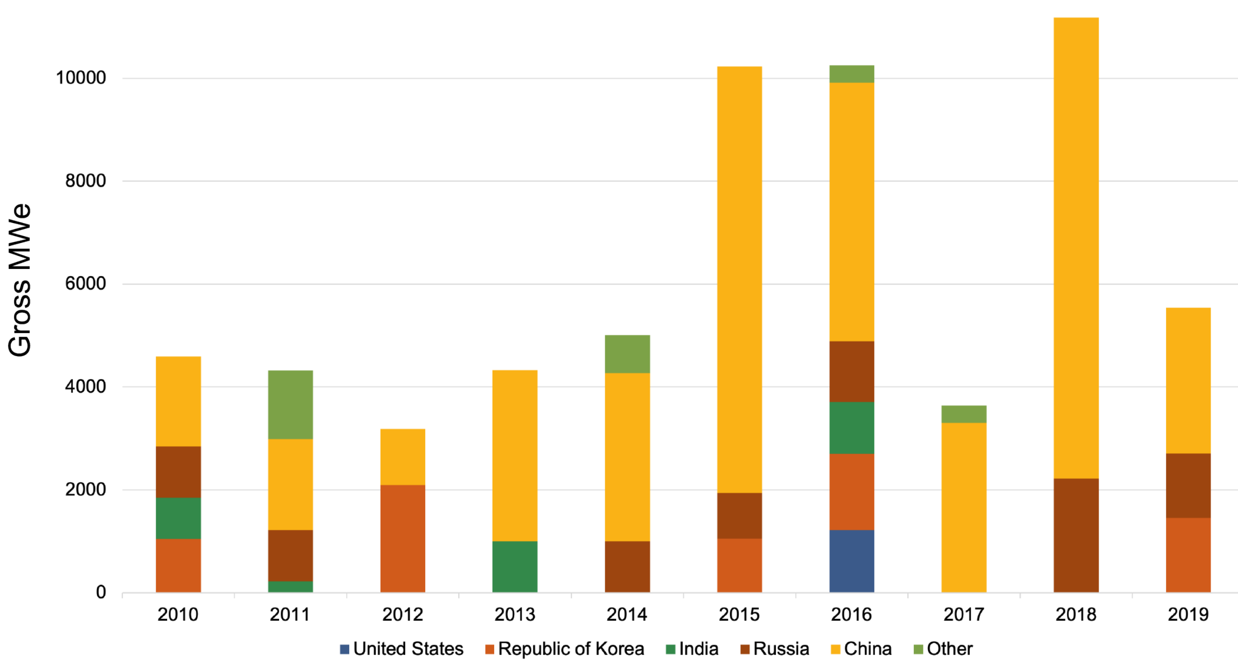

Figure 1.5. Reactor capacity added by year and country, 2010–2019. (Source: Figure from CGEP 2020; data from IAEA PRIS)

Unlike in Russia and China, U.S. nuclear reactor vendors are not government-owned or government-controlled. Private U.S. firms must compete in the global marketplace to win orders. The federal government has many tools at hand to support and expand the domestic nuclear power sector and the commercial technology export sector, including loan guarantees, power purchase agreements, private-public partnerships, and export financing. Since resulting civil nuclear partnerships can lead to other forms of bilateral economic cooperation, the ANS Task Force encourages the use of these tools to counterbalance foreign government sponsorship and keep the U.S. competitive.

Today, advanced reactors with passive safety features promise greater opportunities for U.S. exports to countries with no previous nuclear energy experience. Countries that lack mature training and regulatory frameworks need robust nuclear technologies that are appropriately regulated and operated. Without international leadership and involvement from the U.S., the risks of long-term erosion in global nuclear safety and nuclear nonproliferation norms are significant.[22] By forming R&D partnerships with other nations and providing regulatory training, the U.S. stands to influence the technology choice, regulatory infrastructure, and safety and safeguards standards of "nuclear newcomers."

Federally funded research has enabled past innovations in nuclear plant operations and fuel cycle technologies that are already being used in export markets. For instance, many innovations being commercialized today—including molten salt-cooled reactors, fast spectrum reactors, gas-cooled reactors, and water-cooled small modular reactors—were first conceived in U.S. universities or national laboratories. Our nation's innovation agenda and technology expertise can expand to include non-electricity nuclear energy products and nuclear fuel efficiency.

The economic imperative

Within the U.S., the nuclear energy sector employs nearly 100,000 workers who produce electricity valued at $40 billion–$50 billion each year. On average, each nuclear power station in the U.S. directly supports 500–1,000 long-term, well-paying jobs, and pays more than $80 million in local, state, and federal taxes each year. According to a study by The Brattle Group, the nuclear industry adds $60 billion to GDP annually and contributes $12.2 billion in federal and state taxes.[23] The overall value provided by the civilian nuclear industry is also estimated to contribute more than $42 billion to U.S. national security priorities annually, through human capital, baseload electricity reliability, supply chain, and environmental benefits.[24]

Looking specifically at the more than 70,000 people employed in nuclear power generation and nuclear fuel production, a 2018 Oxford Economics study titled "Nuclear Power Pays: Assessing the Trends in Electric Power Generation Employment and Wages" identified nuclear as the highest-paying industry in the electric power generation sector.[25] This finding was confirmed by another recent report on jobs in the clean energy sector.[26] Furthermore, a report issued in 2020 found that the average mid-wage worker in the nuclear industry earns 22 percent more per hour than the average mid-wage worker in the coal industry, and 25 percent more than a worker in the natural gas industry.[27] The pay differential relative to solar panel installers is even more pronounced: The average installer earns less than half of what the average mid-wage worker in the nuclear industry earns for an hour's work.[28]

In addition to U.S. nuclear plant jobs paying 20 percent more than other energy facilities and employing more workers per MW, a 2020 report found the U.S. nuclear industry has higher union rates than other energy resources—12 percent for nuclear power and 6 percent for fuel jobs.[29]

When nuclear power plants are shut down, the economic ripple effect is severe. Highly skilled workers and their families relocate, demand for local goods and services is reduced, taxes paid to local governments drop dramatically, and housing values erode. These impacts occur at every nuclear power plant but are felt more deeply in rural communities where most plants are located.[30] As a result of both good pay and decades of operation, our nation's nuclear plants have become economic engines for their communities.

Looking internationally, in a 2020 report, the consultancy UxC analyzed global and regional nuclear power outlooks to 2050 based on the scenarios presented in the aforementioned October 2018 IPCC report.[31] UxC used the decarbonization pathways presented in the IPCC report to analyze the types of reactor technologies that could be used in various regions to keep global temperatures at no higher than 1.5°C above pre-industrial levels and estimated that, "the 30-year cumulative total for U.S. nuclear market revenues could range between $1.3 trillion and $1.9 trillion." This projected market share for U.S. nuclear exports through 2050 could take its place in a total global market of $8.6 trillion in estimated nuclear energy expenditures.[32]

In another study, Third Way's *Mapping the Global Market for Advanced Nuclear* forecasted, based on conservative projections, that the global market for nuclear power could triple by 2050 to 7,500 terawatt-hour per year and generate $400 billion of electricity per year.[33] This new nuclear market will be driven by global electricity more than doubling by 2050, with over 90 percent of this growth in the emerging markets of Africa and Asia (see Fig. 1.6). Third Way also found that many of these fast-growing developing countries are ready—or nearly ready—for advanced reactors to help meet their growing energy needs. Furthermore, meeting these countries' demand through civil nuclear trade can lead to other business opportunities in their growing economies.

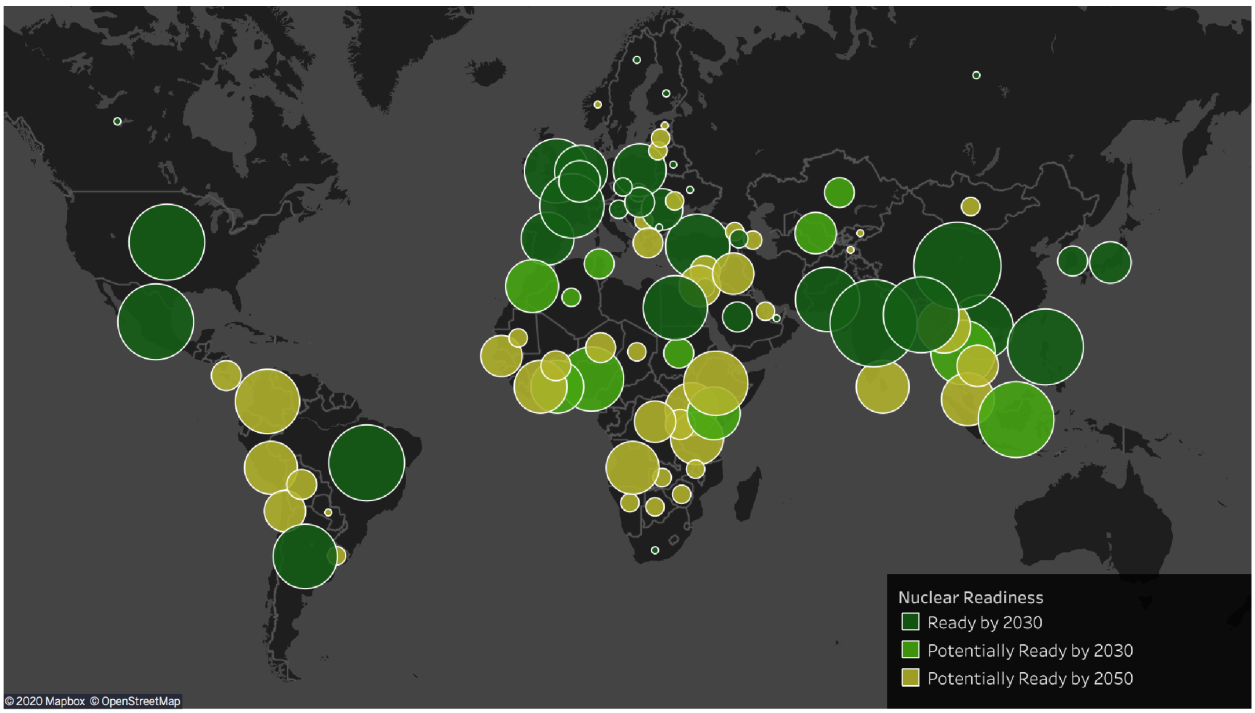

Figure 1.6. Electricity growth from 2017 to 2050 in countries predicted to be ready to host nuclear power plants. (Source: Third Way)

Private U.S. nuclear developers clearly plan to sell their technologies abroad, and increased civil nuclear energy technology exports will produce growth in jobs and economic activity. U.S. suppliers will have opportunities to expand their market presence through new reactor construction projects, maintaining and fueling the global fleet of reactors, and decommissioning aging reactors. To capitalize on these opportunities while satisfying export control requirements, U.S. companies must have clear support from the federal government.

2 A Bright Future for Nuclear Innovation

The United States is poised to field a new set of nuclear technologies in the 2030 timeframe. These technologies can make a major contribution to reducing air pollution and carbon emissions and expanding a world of benefits beyond electricity to industrial applications and nuclear medicine.

Science and technology have already set the stage to reach the national imperatives of clean energy, national security, and economic growth. Critical increases to federal nuclear R&D budgets beginning in the late 2000s acknowledged that nuclear energy is an important part of the nation's clean energy future, and provided a good start.

Today, bipartisan measures have set the stage for private-public partnerships that expand federal nuclear R&D investments beyond universities and national laboratories. Since 2015, a groundswell of interest and support from private companies and a number of nongovernmental organizations has continued to grow. The DOE recognized the need to support the fledgling efforts and launched the Gateway for Accelerated Innovation in Nuclear (GAIN) in 2016. Recognition of the importance of nuclear technologies at the national level was also reflected in the bipartisan congressional support for the Nuclear Energy Innovation Capabilities Act (NEICA) and the Nuclear Energy Innovation and Modernization Act (NEIMA), which were signed into law in 2018 and 2019, respectively. NEICA and NEIMA directed the DOE and the Nuclear Regulatory Commission (NRC) to emphasize new technologies, new testing facilities, and regulatory modernization. Figure 2.1 illustrates total U.S. energy research, development, and demonstration spending over more than four decades and provides a historical context for these recent nuclear R&D investments.

Other pieces of legislation, such as the Nuclear Energy Leadership Act and the Nuclear Energy Research and Development Act, were incorporated in the historic Energy Act of 2020—the first major piece of energy legislation in over a decade—while the American Nuclear Infrastructure Act, introduced at the end of 2020, has also received bipartisan support. Together, these pieces of legislation target multiple projects and programs to support existing nuclear reactors and to advance the next generation of nuclear technologies. For example, the Fiscal Year 2020 Energy and Water appropriations initially directed the DOE to select several advanced reactor designs for support through the Advanced Reactor Demonstration Program (ARDP).[34] The ARDP is one way the federal government is ensuring that its investments will lower costs and shorten the development time for advanced reactors. By authorizing the ARDP, the Energy Act of 2020 has cemented its importance.

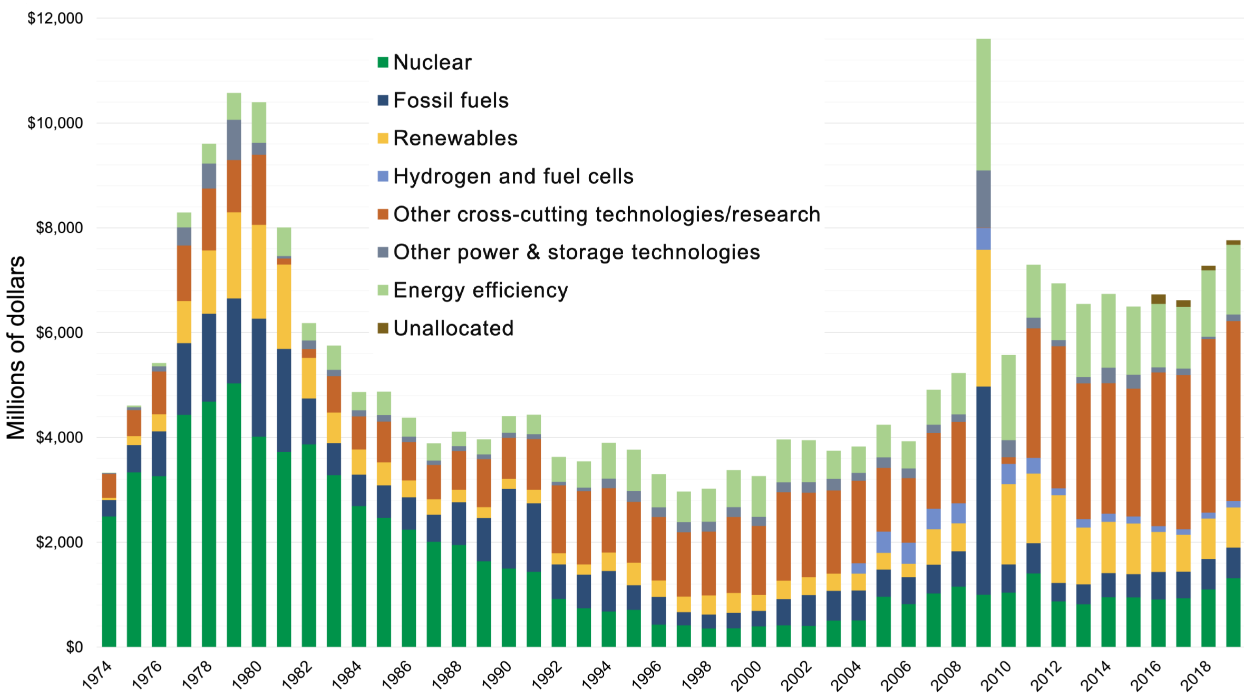

Figure 2.1. Total U.S. energy research, development, and demonstration spending, 1974–2019, at 2019 prices and exchange rates. (Source: International Energy Agency)

Advanced reactors

Advanced reactors are being developed with a wide variety of fuels, operating temperatures, and sizes, and offer several potential advantages over large light-water reactors. Small modular reactors (SMRs), for example, take advantage of simplified reactor design and increased use of factory fabrication to reduce costs and construction times.[35] Advanced nuclear assets can function as baseload power with 24/7 availability or as dispatchable power on an as-needed basis. In addition, advanced reactors are designed for flexible operation modes, such as thermal energy storage, which allows them to partner with intermittent sources of power like wind and solar to ensure grid reliability.[36,37]

The characteristics of advanced nuclear reactors enable effective scaling and make them a candidate for electricity systems that have not traditionally included nuclear energy. Large-scale deployments at or near 1 gigawatt remain an attractive option for larger countries with major users, including utilities, where economies of scale benefit a centralized, baseload model. Mid-range deployments of a few hundred megawatts are effective options for end-users that need to limit upfront capital investment or end-users that have a lower capacity need. These units would be efficient uses of capital because of their potential to repower some existing fossil-generation sites. In addition, smaller countries that cannot support gigawatt-scale reactors on their grids may find these mid-range reactors to be appealing low-carbon options. Small-scale or distributed energy resource reactors,

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commonly called microreactors, produce 20 megawatts or less. Microreactors can serve niche, high-value markets, such as remote military bases or mining sites, for mission-critical applications.

The value proposition for SMRs is exemplified by the vulnerabilities of the electricity grid in Puerto Rico, which is dependent on imported fossil fuels and has been crippled by hurricanes. A group of Puerto Rican engineers recently formed the nonprofit Nuclear Alternative Project (NAP) to study the prospects for advanced reactor deployments in Puerto Rico, and in 2019 was awarded a grant from the DOE's Office of Nuclear Energy to perform a preliminary feasibility study on the use of advanced nuclear technology on the island.[38] The study assessed market conditions, the legal framework, existing infrastructure, and public perceptions of nuclear energy, and concluded that small modular reactors and microreactors could make substantial contributions to a diverse zero-emission energy mix for Puerto Rico.

Importantly, microreactors and SMRs show unique promise for a reliable energy future in niche applications due to advances in design and technology that facilitate higher efficiencies and more compact designs. As an example, the Department of Defense has identified a growing need for mobile microreactors to supply on-the-spot electricity to energy-intensive military operations. Through Project Pele, the DOD awarded three contracts in 2020 for the design of a microreactor that can fit inside a standard shipping container.[39] Such microreactors could also serve communities in remote regions of the country. In addition, the U.S. Air Force expressed interest in using a stationary microreactor to power a remote base.[40]

In addition to meeting varied needs by tailoring the size of the reactor, the heat from nuclear plants can also be used for other needs. As shown in Figure 2.2, integrated energy systems can use nuclear plants to provide dispatchable electricity to the grid and provide heat energy, or store heat for use at times of high demand. Design diversity allows customers to choose an advanced reactor that

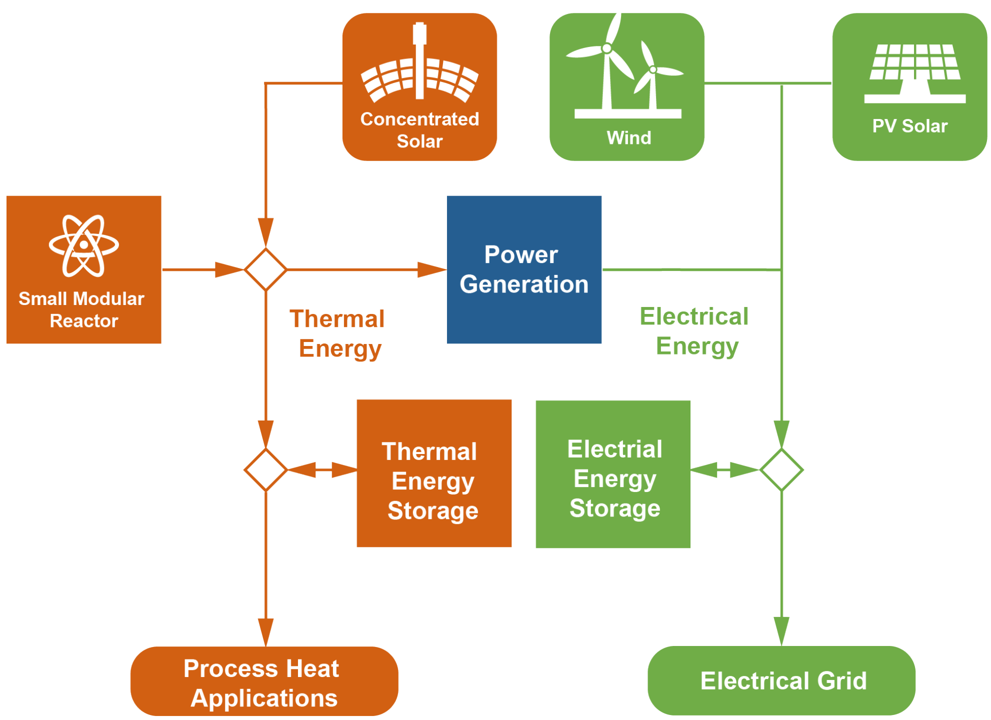


Figure 2.2. Integrated energy systems take a hybrid approach to nuclear and renewable sources. (Source: Nuclear Innovation Alliance 2017)

can provide the output best suited to local energy needs, which could include both electricity and heat for residential heating, hydrogen production, desalination, or a broad range of industrial processes.

Medical and other uses of nuclear technology

The medical community relies on radioisotopes and radiopharmaceuticals to diagnose and treat cancer and other diseases. DOE researchers and nuclear test reactors provide significant capabilities for isotope discovery and generation, as do university research reactors throughout the nation. Therapeutic radioisotopes require a sizable production ramp up from research to drug trials to full production on financially viable timelines. Getting NRC and Food and Drug Administration approvals for a new medical radioisotope requires an organized approach by the U.S. government, nuclear industry, medical providers, and pharmaceutical companies. Government investment will foster new therapeutic discoveries and streamline the introduction of those products to the medical community to help save lives.

Nuclear technologies also play a significant role in ensuring the health and safety of our food supply and sterilizing medical supplies, including personal protective equipment.

Reimagining the energy supply system

Maximizing efficient electrification of emissions-heavy sectors such as transportation and industry is necessary to achieve a net-zero carbon economy. Almost every major auto manufacturer in the world has committed to electrification of their products. Volkswagen has promised full electrification of its portfolio by 2030, and Honda has committed to make plug-in electric vehicles (EVs) two thirds of its production by 2030. More recently, GM announced that it plans to make its global products and operations carbon neutral by 2040.

Electrification will only truly drive emissions reductions when the electric grid is fully decarbonized. The aggregate increase in electricity demand resulting from the likely expansion of EVs is significant. Our power grid will need to provide an average of 3.8 MWh of electricity each year for each

FUSION ENERGY

Fusion could drive transformative change by providing an abundant, zero-carbon energy source. Similar to fission, fusion energy has the potential to be used not just for electricity generation, but also as a process heat source for desalination, hydrogen production, chemical production, or other industrial applications. Fusion is also a strategically important technology for the U.S. to develop domestically, given its potential for spin-off technologies in fields including superconductors and advanced materials and for future applications of its uniquely high energy density.

Harnessing fusion for sustained energy generation has proven to be a formidable task. Existing DOE fusion R&D activities are largely oriented toward achieving a sustained burning plasma, which is the goal of the International Thermonuclear Experimental Reactor (ITER) as well. While fusion has yet to achieve a net energy gain, several private companies are pursuing different technologies to commercialize fusion energy.[41] The ANS Task Force concurs with the recent draft report from the Fusion Energy Sciences Advisory Committee (FESAC), *Powering the Future: Fusion & Plasmas*,[42] which details the need for demonstration opportunities for commercial fusion technologies that can be used for power generation. Commercial fusion has tremendous potential to produce zero-carbon electricity, thus support from the DOE Office of Science is justified. However, the Task Force determined that specific funding recommendations and timelines for fusion R&D were beyond the scope of this report.

EV added to U.S. roads.[43] A recent study by a group of national laboratories, auto manufacturers, and energy providers found that EV-driven incremental power demand may grow by as much as 25–27 TWh each year between 2030 and 2040. That annual increased demand is equivalent to more than one third of all the electricity generated by solar panels in the U.S. in 2019.[44]

Further emissions reductions from the transportation and industry sectors will require a reliance on energy-dense clean fuels, clean feedstock, and clean heat in addition to clean electricity. Flexibility in operations, scale, and energy production make advanced nuclear a key technology for enabling this broad range of non-electric applications.

Hydrogen (or equivalent hydrogen-based energy carriers such as ammonia) is the preferred replacement to natural gas as a distributed clean fuel. Advanced nuclear reactors can produce the high-grade heat (500°C or above, with some designs reaching up to 750°C) that makes hydrogen production more efficient.

FOUNDATIONAL CAPABILITY

The DOE Office of Nuclear Energy maintains nuclear capabilities that NASA, the Department of Defense, and the DOE's National Nuclear Security Administration (NNSA) rely on to carry out their missions. The Nuclear Energy portfolio funds in-depth and cross-cutting nuclear research, provides unique R&D infrastructure, and ensures safeguards and security are in place to protect these missions and minimize duplication of efforts across agencies.

NASA space exploration

As the desire for an enduring presence on the lunar surface and on Mars grows along with aspirations for space industrialization, additional space propulsion and power systems will be needed. To prepare, NASA and the DOE are working with industry to design systems to provide kilowatts and eventually megawatts of electricity in space. New nuclear technologies, specifically fuels and energy conversion systems, have allowed space applications to stretch beyond historical limits, justifying optimism that the U.S. can meet near-term objectives for space exploration and ramp up to higher power levels when needed. The U.S. government has been a world leader in the use of radioisotope thermoelectric generators to power space exploration and scientific missions. Like past space missions, nuclear propulsion—either thermal or electric—will create a host of new technical advancements here on earth.

Microreactor missions

Department of Defense operations at remote military bases increasingly rely on electricity and electronics, and the DOD is looking to mobile microreactors to supply that electricity. The DOD awarded three contracts in March 2020 through Project Pele for the design of a mobile microreactor that can fit inside a standard shipping container. After a two-year design-maturation period, one of the three teams may be selected to build and demonstrate a prototype. Through Project Pele and other work, the DOD is leveraging DOE technologies and providing an initial market for both mobile and stationary microreactors, funding a technical demonstration that will serve to reduce schedule and cost uncertainty for commercial deployments.

National Nuclear Security Administration

The NNSA, a semi-autonomous agency within the DOE, needs nuclear science to maintain and enhance technologies for national defense. The understanding and application of nuclear energy is inextricably linked to the safety, security, and effectiveness of the U.S. nuclear weapons stockpile; countering the global danger from weapons of mass destruction; safe and militarily effective U. S. Naval nuclear propulsion; conversion of research reactors from highly enriched uranium (HEU) fuel to high-assay low-enriched uranium (HALEU) fuel globally; and responding to nuclear and radiological emergencies in the U.S. and abroad.

3 Reducing Economic and Technological Barriers to Success

The products of an innovative nuclear R&D pipeline must be fueled, maintained, and recognized for the clean, reliable energy they provide to ensure that cost-competitive nuclear technologies can enable a global clean energy future.

Energy technology applications are continually changing, and nuclear stakeholders must develop ways to incorporate new concepts and materials. Whether ideas originate in universities, national laboratories, or private companies, they face barriers to market entry, including regulatory approvals, time to deployment, and the high cost of capital.

New technologies and equipment are being brought to bear to solve these problems. For example, computational resources available today enable a sophisticated modeling of materials that can accelerate development and refinement of reactor designs, and special test reactors can quantify the performance of advanced fuels under operating conditions and off-normal conditions. Following are some notable research needs that are being addressed through ongoing, federally funded investments.

Improved advanced nuclear economics

A study by LucidCatalyst found that capital costs of less than $3,000/kW make nuclear energy an attractive clean energy investment.[45] DOE programs, including advanced manufacturing and advanced construction techniques such as digital twins, should be focused on developing reactors that can meet cost targets that allow nuclear to be a key tool in decarbonization.

In order to achieve these cost targets, nuclear capital costs need to decrease. Combining advances in manufacturing technologies, including potential private-public partnerships with traditionally non-nuclear entities like shipyards, can provide new pathways for mass production.[46]

Today, the DOE is focused on making nuclear technology cost-competitive in electricity markets through integrated energy systems for both existing and advanced nuclear reactors,[47] but R&D programs also need to be focused on making nuclear production of hydrogen competitive with existing steam methane reforming production. As the DOE creates R&D opportunities, they need to be responsive to changes in the market so these programs can lead to the deployment of clean, reliable nuclear energy.

A sustainable existing nuclear fleet

Economics are also key to realizing the clean energy benefits of existing nuclear power reactors. The current reactor fleet contributes nearly 20 percent of the electricity generated in the U.S. Sustained operation of the current U.S. fleet of 94 operating reactors provides fuel source diversity, energy reliability, and economic value. Sustained operation is made possible by maintaining and monitoring vital structures, systems, and components, and by achieving viable economics in current and future energy markets. With several utilities planning to operate their nuclear units beyond 60 years, R&D programs are needed to ensure those reactors can operate economically and safely.

The DOE's Light Water Reactor Sustainability Program has been and will continue to be a key program addressing those needs through research into:

- Component aging and optimal replacement schedules
- New instrumentation and control systems, including condition monitoring and machine learning applications that reduce operational costs
- Technical and economic aspects of integrating nuclear power plants with industrial processes to supply additional energy products
- Optimization of safety margins and reduction of uncertainty through advanced risk assessment tools that allow for regulatory flexibility
- Alternative materials for component replacement that lower operating costs
- Tools for optimizing the cost-effectiveness of physical security

Maintaining electricity production from these existing low-carbon generation sources while new low-carbon sources are developed and brought on-line is essential if the U.S. is to meet its near-term goals for carbon emissions reduction.

Fuels for existing and future reactors

When it comes to advanced nuclear energy systems, a lot of attention gets focused on reactor designs. Each of those designs relies on a nuclear fuel cycle that begins with sufficient fissile material to support sustained nuclear fission and ends with the safe, environmentally responsible disposal of radioactive byproducts from the fuel and reactor. Sources of fissile material include uranium-235 mined from the ground and concentrated through enrichment, plutonium recycled from reactor fuel or repurposed from a weapons program, or even uranium-233 bred from thorium. The fuel itself can take many forms—a solid oxide or metallic fuel, self-contained TRISO pellets, or dissolved in molten salt, for example. Used fuel can be deposited directly in deep geological formations or recycled to recover useful material and minimize the volume of the remaining radioactive byproducts requiring disposal. Some reactor technologies plan to use existing stockpiles of used fuel as a cost-competitive fuel source. The nuclear industry has substantial experience with the once-through fuel cycle typically used for light-water reactors. Mining, milling, conversion, enrichment, fabrication, storage, transportation, and aqueous recycling are all proven on an industrial scale, and deep geologic disposal programs are in final siting and construction phases overseas.

Economic, environmental, security, and policy considerations will determine ultimate fuel cycle approaches. These choices are informed and supported by R&D conducted at national laboratories, universities, and industry. Ongoing work includes the near-term development of advanced, accident-tolerant fuel for existing light-water reactors; TRISO and metallic fuels qualification for advanced reactors; research into advanced separations technology for used fuel; and demonstration programs for long-term storage of used fuel. The energy density of high-assay low-enriched uranium (HALEU) can make future fuels for existing and advanced reactors more efficient, and will permit advanced reactors designs to be more compact than large light-water reactors. There is currently no commercial source of HALEU. Recognizing a critical need, the DOE has taken steps to spur the commercial production and transportation of HALEU. In addition to supporting deployment of new fissile power systems, ongoing fuel cycle R&D supports America's national security and nonproliferation objectives and must receive sustained support if the U.S. is to be a leader in nuclear technology worldwide.

WHAT ABOUT THE WASTE? "They don't know what to do with the waste." It's a standard criticism of nuclear energy, one that the nuclear industry has done a poor job of explaining.

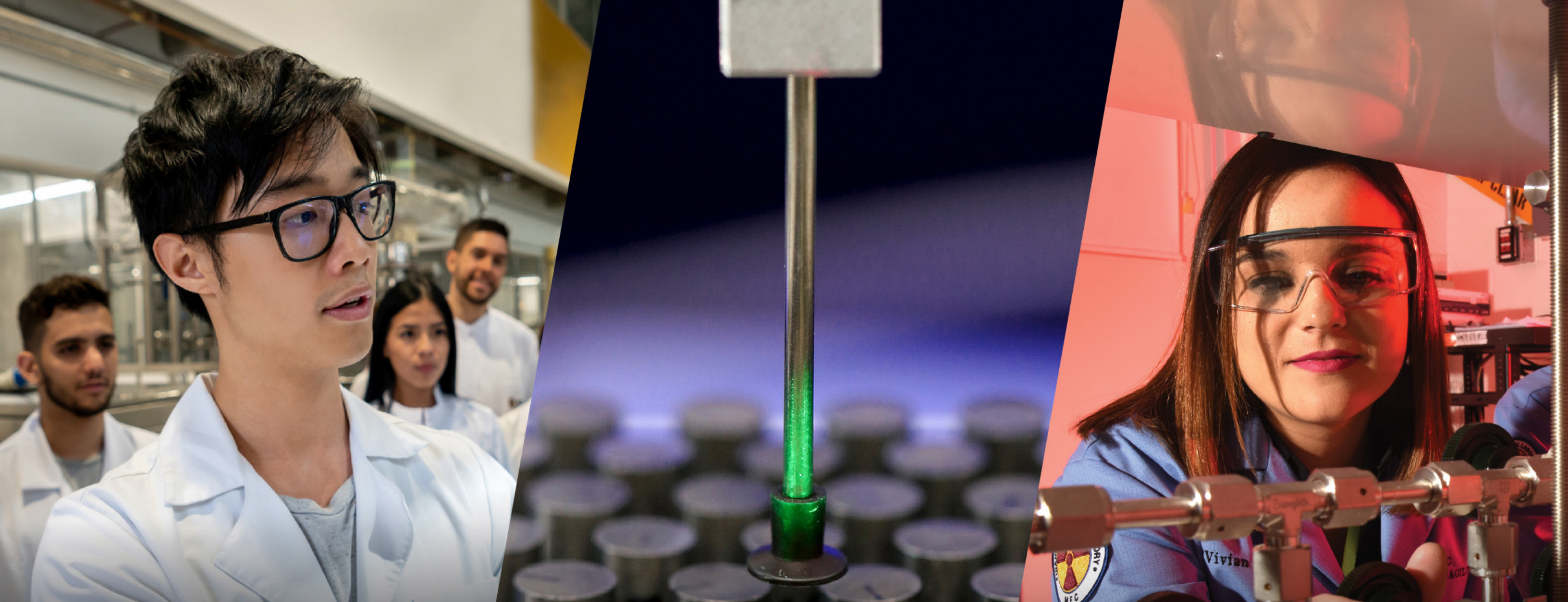
In fact, the U.S. does have a functioning system to safely manage nuclear waste from its nuclear plants. Low-level radioactive waste is compacted and shipped to regulated facilities for disposal. Highly radioactive waste materials, such as used fuel, are small in volume and exist in solid, stable forms. Used fuel is stored at reactor sites, first underwater in secure pools and then in robust, passively cooled dry storage systems.

The U.S. nuclear waste management system is missing one important piece, however: a long-term geologic repository. Like most other nations with nuclear plants, the U.S. has elected to dispose of its commercial used fuel directly in deep geologic formations, isolated from the environment. The site Congress has chosen for the U.S. repository, Yucca Mountain in Nevada, has been stalled by state opposition.

Unlike the U.S., other nations have moved forward with geologic repositories, including one currently under construction in Finland and another nearing that stage in Sweden. France recycles its used nuclear fuel, so the volume of their waste requiring long term disposal is significantly lower than in the U.S. Recently, a start-up began developing an innovative borehole-based alternative for disposal, using advanced drilling technology repurposed from the oil and gas exploration industry. Some proposed advanced reactor technologies would recycle used fuel that is currently characterized as waste.

In short, there are multiple, proven methods for managing nuclear waste, as well as over $40 billion in a federal fund established for that purpose. What's missing is an up-to-date set of federal policies to make progress. The American Nuclear Society has identified a set of technical, regulatory, and programmatic actions Congress and/or the Administration can take to make near-term progress on waste management.[48]

For purposes of this report, the ANS Task Force included roughly $1.1 billion in ongoing R&D for generic waste disposal, handling, storage, and transportation. The requirements and funding for the national program for used fuel and nuclear waste management (development, licensing, construction, and operations of the storage, transportation, and geologic disposal system) are not included in our report and await policy direction from the Administration and Congress.



4 Structuring R&D Programs to Create an Innovation Pipeline

Bipartisan support in Congress and the administration has established the foundation for a vibrant U.S. advanced nuclear technology sector. However, continued U.S. leadership will require an expanded suite of experimental facilities along with a robust pipeline of research, development, and demonstration activities, all dedicated to the goal of continuous nuclear innovation.

The nuclear imperatives of clean energy, job creation, and national security require a strong U.S. nuclear enterprise. To build that enterprise effectively, nuclear R&D programs must fund new ideas and facilitate the maturation of concepts into reactors that are cost competitive with other sources of energy. Such maturation programs include separate effects and integral experiments, along with modeling and simulation to interpret and build upon experimental results and obtain performance data necessary for regulators. Also important are programs that support the acquisition and analysis of performance data to enable fine tuning to ensure the maximum service, safety, and efficiency of existing and future assets.

In addition to technical advancements, robust nuclear R&D programs are critical to educate and build the next generation nuclear workforce. Scholarships and fellowships sponsored by federal programs are important to bring new U.S. students into the field, enabling industry and government alike to recruit talent into their companies, laboratories, and agencies. Support for relevant social and behavioral sciences programs can go a long way to stimulate communication and understanding between all communities and stakeholders about the benefits of nuclear technologies, building a strong foundation for civic partnerships.

These diverse needs must be recognized when structuring federal R&D programs to optimize the value of the investment and reap the value that only nuclear energy can provide. Benefits accrue from supporting reliable nuclear technologies. Safe and efficient advanced reactors can attract international financial support, thus reducing the need for federal support while fostering cost-effective international scientific collaborations.

Also, for the nuclear enterprise to survive and thrive, an ecosystem supporting all technologies of the nuclear fuel cycle is necessary to successfully realize the benefits of nuclear energy for multiple applications. From the front end conversion and enrichment of nuclear fuels, the production of heat or beneficial isotopes from fissile and fertile materials, the conversion of fission-generated heat to electricity or industrial process heat, and the back end nuclear processing to recycle or store spent fuel, the nuclear fuel enterprise draws on many disciplines and complex engineering to manage materials operating in harsh conditions.

Today, private developers are moving multiple advanced nuclear technologies toward commercial deployment.[49] Building on work that began with substantial federal funding in the era of Atoms for Peace, advanced nuclear developers are aiming at many new market opportunities and a broader set of needs are driving examination of new coolants and configurations. Better understanding of materials, physics phenomena, and neutron irradiation enable more sophisticated designs. The readiness of different nuclear concepts varies, with some developers aiming for deployment within this decade, while others target deployment in the next decade.

A 21st-century funding strategy needs to take a holistic approach to recognize and address diverse needs. Successful R&D programs can lead to the private-public partnerships that are necessary to realize new first-of-a-kind advanced reactors. But funding mechanisms for other technologies, such as the mitigation, reuse, or disposal of radioactive waste, may require significant oversight to ensure safeguards for safety and proliferation. These programs may merit federal support to develop concepts that are in large part, or wholly, managed by the government.

Whether pursuing a reactor, a treatment process, or interim or permanent storage of used fuel, U.S. developers and national research organizations must be supported by a network of world-leading capabilities for performing specialized testing, analysis, development, and deployment.

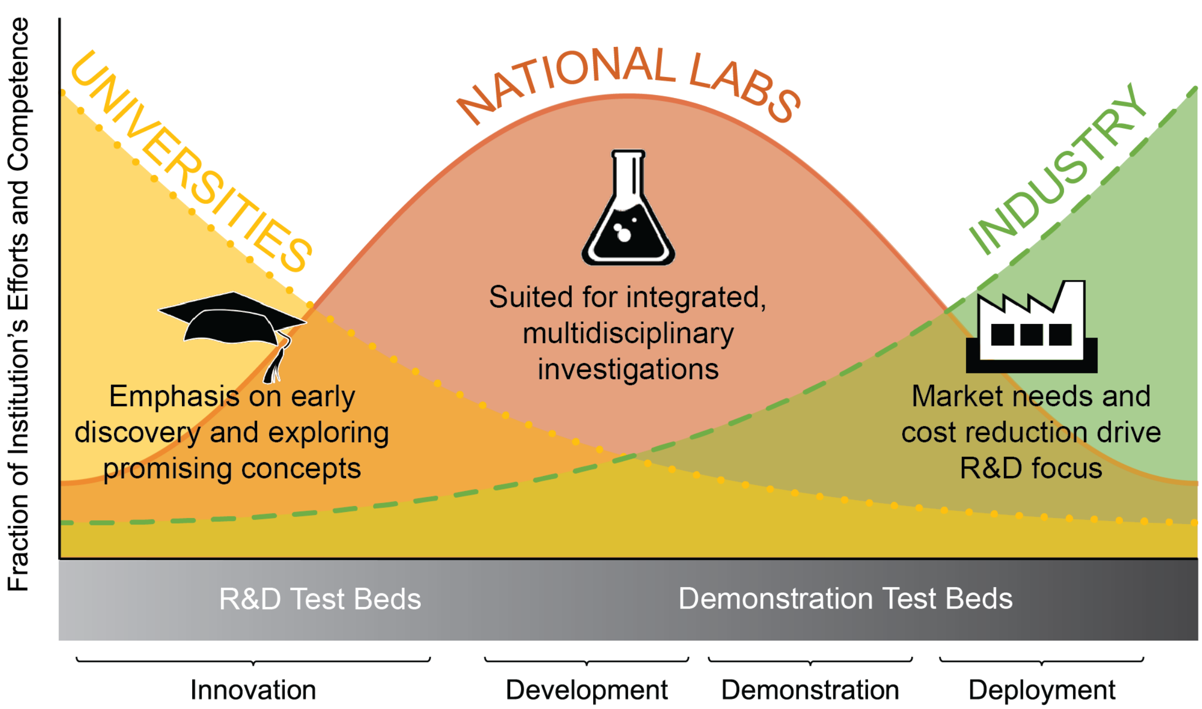


Figure 4.1. The research ecosystem for nuclear technology development.

A representation of the research and development ecosystem is captured in Figure 4.1. Concept maturation progresses from left to right, and a notional mix of contributions in three institutional sectors is captured graphically in color: yellow for universities, red for national laboratories, and green for industry. As a concept matures, foundational science and innovation moves through the R&D life-cycle to become a product, which may be a tangible product like a nuclear reactor, or perhaps a chemical process to isolate and vitrify long-lived radioactive waste.

The relative contribution of the institution type shifts as different competencies are needed to advance from a concept to an end product. Universities, national laboratories, and industry all germinate ideas and may initiate early innovation and participate all the way through to market deployment. However, each type of institution has a different primary focus, and universities generally dominate early in the cycle, national laboratories in mid-cycle, and industries at the end of the cycle. All require a robust set of testing capabilities to support research innovation, development, demonstration, and deployment.

The descriptions below articulate characteristics of a revitalized U.S. nuclear enterprise that rests on a foundation of technical capabilities and nurtures viable concepts to deployment:

Build and maintain a foundation of capability: Provide national R&D test beds as well as demonstration test beds of cutting-edge experimental capability, computational capability, and databases, and staff those activities with people who have the expertise to keep the test beds flexible and relevant. U.S. nuclear technology test beds are distributed across multiple facilities at federal laboratories, universities, and commercial entities, and include both specialized facilities and large, capital-intensive demonstration facilities. The nation's primary neutron-generating test beds currently include the Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), the High Flux Isotope Reactor (HFIR), and the MIT Reactor (MITR), and they need to remain accessible and at the highest caliber. The Versatile Test Reactor (VTR) will add a fast-spectrum neutron source to the suite of U.S. nuclear technology test beds to provide needed data for technology developers and scientists from all over the nation. The VTR will help reestablish U.S. global leadership in nuclear energy R&D, while attracting potential collaborations, investments, and personnel from international research partners.

Motivate innovation: Encourage germination of new ideas through long-term basic science and associated investment, particularly in materials, chemistry, computational science, systems science, nuclear physics, and plasma physics. Making many modest investments in exploratory ideas will create an atmosphere where transformational concepts can emerge. Programs providing competitive awards, such as the Nuclear Energy University Program (NEUP) and industry-led cooperative agreements, are magnets for new talent and attract young leaders who care about promoting clean energy, national security, and public health. Innovation projects can explore new uses for nuclear technology or more economic utilization of current technology, with cost-competitive future deployments as a key goal. These programs should include the intersections of technology with the social sciences to understand the factors that lead to technology acceptance.

Develop promising concepts arising from innovation: Provide access to technical, regulatory, and financial support to move innovative technologies toward commercialization and optimize the use of existing assets by focusing on technology challenges that, when solved, will benefit multiple stakeholders. Development programs could include putting cutting-edge technologies such as 3D printing, machine learning, artificial intelligence, and data mining to use in nuclear systems. Concepts must meet milestones and pass metrics in order to advance to deployment. For example, those that do not show feasibility or scalability may be required to go through another iteration of development and would not advance to deployment without evidence of progress.

Accelerate the deployment of first-of-a-kind technologies: Facilitate the commercialization of technologies by the private sector by recognizing the unique needs of private partners and host communities to overcome first-of-a-kind technical, regulatory, and financial risks. Programs may include siting demonstrations at federal laboratories or universities, technical support such as data qualification, financial cost sharing, and advancing the social science of community technology acceptance. This work should set the stage for large-scale buildout and deployment of commercial technologies. During this phase, market pull must be evident.

Ensure regulatory readiness as the technology advances: Proactively develop channels of communication with applicable regulators to allow early assessment of new innovations, while keeping the focus on protection of public health and safety. The enterprise must provide the means, perhaps through non-fee-based funding, for regulators to equip their staff with the skills to make timely decisions on new technologies and concepts and engage in frequent communication with nuclear developers, so that a regulatory framework for advanced reactors is in place when needed.

Provide a well-coordinated governmental system: Ensure deployment of U.S.-led technologies in the international marketplace is undertaken as a coordinated federal interagency effort so that potential customers receive the assistance they need, financing is available, and safeguards and security principles are transmitted along with the technology.

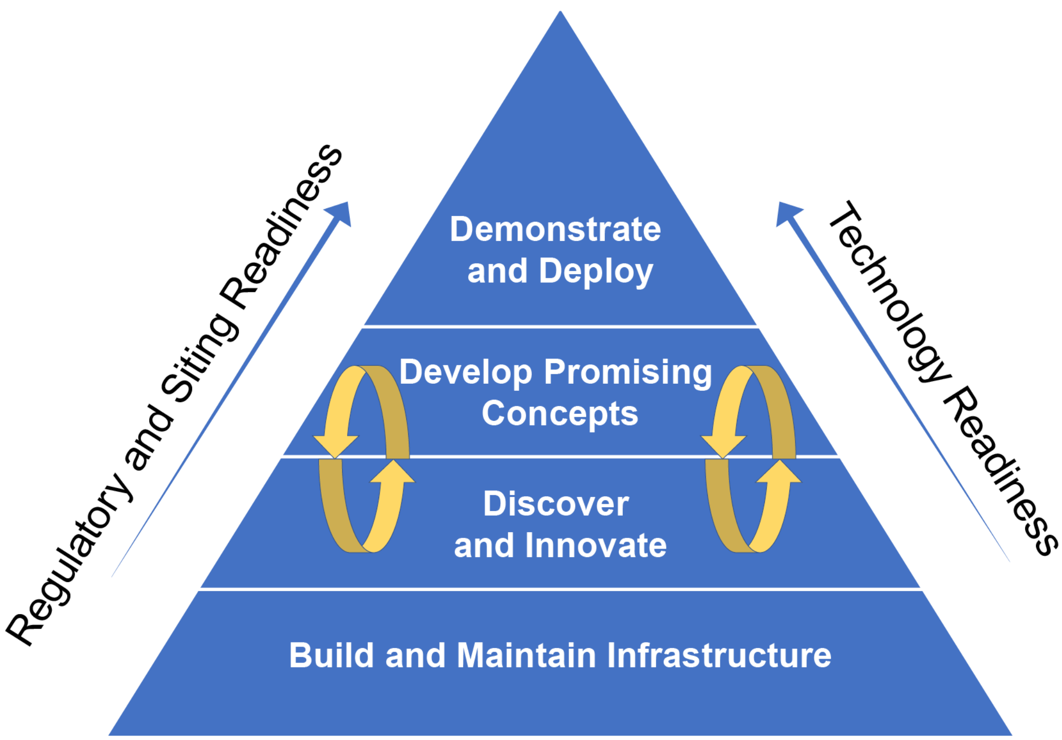


Figure 4.2. A progression of federal R&D program components.

The Innovation Pipeline

Every concept, be it an advanced nuclear reactor, fuel type, or waste form, passes through a notional pipeline as it matures to commercial deployment. Figure 4.2 illustrates this pipeline as a funnel that channels ideas from the bottom to the top. Ideas are conceived within the "discover and innovate" phase, supported by resources in the "build and maintain infrastructure" phase. As concepts are refined through development and iteration, they progress upwards, and viable concepts are winnowed down to a smaller set of vetted concepts that have the potential to become deployed products.[50]

A healthy innovation ecosystem always has multiple ideas in the funnel—from early innovation to commercial deployment. Federal research programs feed new ideas, help answer key development questions, and support first-of-a-kind technologies to commercial deployment. To maintain an innovative technology lifecycle, the NRC must also take a flexible approach to evaluating and licensing advanced nuclear technologies while maintaining its focus on protection of public health and safety.

Any one technology will pass through different stages of funding to reach maturity. A successful federal innovation program establishes private-public partnerships at each level of this innovation process, and five types of programs are necessary:

- **Capability programs** build and maintain infrastructure to ensure the U.S. research community always has "best in class" research tools and data. They support physical capabilities and the staff who maintain and improve them.
- **Innovation programs** enable, stimulate, and facilitate advances beyond the current state of the technology. These projects are often focused on materials

ADVANCED RECTOR DEMONSTRATION PROGRAM

To support demonstrations of advanced reactor technology, the DOE launched the Advanced Reactor Demonstration Program (ARDP) in May 2020. The philosophy of the program is consistent with the pipeline phases described in Figure 4.2. The program provides access to national capability and cost-share funding for concepts at different levels of funding depending on the development readiness of the concept. Industry participation requires a cost share to match the federal dollars, increasing from 20 percent to 50 percent in recognition that successful companies will gain a new revenue-generating technology. As outlined by the DOE, there are three levels:

Advanced reactor demonstrations, which are expected to result in a fully functional advanced nuclear reactor within seven years of the award. In October 2020, the DOE announced agreements to support demonstrations of X-energy's Xe-100 high-temperature gas reactor and TerraPower's Natrium sodium-cooled fast reactor.

Risk reduction for future demonstrations, which aims to resolve technical, operational, and regulatory challenges to prepare for future demonstration opportunities. In December 2020, five teams—led by Kairos Power, Westinghouse, BWXT, Holtec, and Southern Company—were selected to receive risk reduction awards.

Advanced reactor concepts 2020 (ARC 20), which will support innovative and diverse designs with the potential to commercialize in the mid-2030s. Awards were announced for three teams in late December 2020: ARC Clean Energy, General Atomics, and the Massachusetts Institute of Technology.

The ARDP will leverage the national research capability through the National Reactor Innovation Center. This structure provides greater funding for a smaller number of concepts as their commercial readiness increases. This same philosophy can apply across the research spectrum.

or computational modeling and simulation tools, and are typically carried out on a bench scale to study separate effects phenomena.

- **Development programs** build out promising technologies from seed ideas that often include concepts already explored in innovation programs. Work in these programs is a mix of experiments and modeling and simulation to provide data for national databases and predict technical performance. Projects are often multi-disciplinary because of the integral testing and the modeling and simulation required for complex systems and sub-systems. These projects have longer time horizons and larger budgets than innovation programs.
- **Demonstration and deployment programs** prove viability of integrated systems by advancing technologies until a customer or investor has enough information and data to continue forward to deployment, or to end the project if it is not economically viable. Deployment mechanisms assist first-generation technologies as they enter commercial operation. They include items such as power purchase agreements, tax incentives, and clean energy portfolio standards to support and accelerate growth.

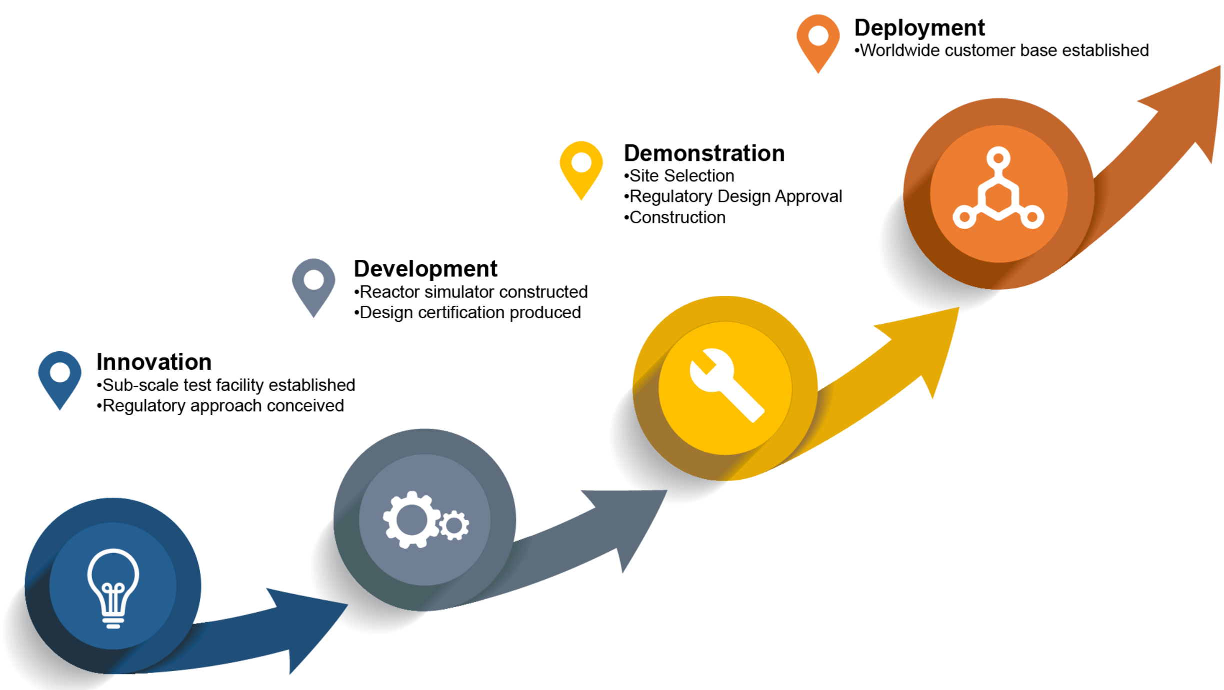


Figure 4.3. A notional progression of advanced reactor development.

Figure 4.3 illustrates how advanced reactors can progress to deployment and lists representative activities undertaken at each step.

Not every idea will be successful. Thus, a merit-based downselect process is envisioned to use evaluation criteria and guidelines to winnow ideas with promise to those with the demonstrated success necessary to be competitive in the marketplace. Guidelines include:

- Fund projects that result in reduced costs to deploy nuclear technologies.

- Decrease the number of supported concepts as technologies progress to enable an increase in public funds for those technologies selected for demonstrations. The choice of private demonstration partners is strongly supported by evidence of commercial interest.
- Shift the primary funding support from the government to private or investor funding as the product matures in technology and licensing pathways. While public funding peaks during the demonstration phase, private funding increases throughout the process and peaks at deployment. Some developers may pursue commercialization with private funding and little or no need for direct public funding. These pathways should be examined and supported appropriately as well.
- Oversee the federal investment in private-public partnerships by critically examining technology progress at each level. The federal government could tap into technical experts from national laboratories and universities for the evaluations.
- Support and facilitate advancement of seed ideas from any source (university, laboratory, and industry) and include advanced nuclear reactor technologies as well as associated novel technology uses beyond gigawatt-sized electricity production facilities that may inspire important research programs.
- Identify key milestones to be assessed at decision points and offramps.

Under this approach the government responds to private investment activity, demonstrated technology viability, and commercial interest. For example, a "payment for milestones" approach, which the Nuclear Innovation Alliance has called "SpaceX For Nuclear", could allow federal investments to follow measurable deliverables along the development path.[51] The Energy Act of 2020 authorized the DOE to use milestone-based demonstration projects. It is now incumbent on the DOE and the Office of Nuclear Energy to determine how to successfully implement such projects for nuclear energy. The ANS Task Force recommends incorporating best practices and lessons learned from NASA's Commercial Orbital Transportation Services (COTS) program and reaching out to organizations like SpaceX and nuclear technology developers to understand how to best support participants in these projects.[52]

Mapping current programs to the pipeline

To adequately sustain a thriving nuclear R&D test bed and ecosystem, every phase of the innovation pipeline must be valued and funded. The goal is to achieve balance in the system to enable production of a continual stream of new products. Overcommitting to one phase over others may provide a temporary gain (such as a flood of new innovation ideas) but, in the long-term, would be a detriment to balanced progress.

The following descriptions map how current programs could fit in an innovation pipeline.

Capability

Builds new unique national capabilities; maintains, secures, and optimizes the operations of current facilities; provides time for research staff to create new approaches to using the current facilities; and supports the human resources development that attracts and develops a next generation of researchers.

The National Reactor Innovation Center (NRIC), Gateway for Accelerated Innovation in Nuclear (GAIN), and Nuclear Science User Facilities (NSUF) are three different programs intended to make national research and demonstration capability available to researchers and reactor developers. For these programs to be successful, the U.S. needs to maintain a set of uniquely capable national facilities. These programs recognize the tremendous value associated with test reactors, hot cells, high-performance computing facilities, national peer-reviewed databases, and other unique capabilities.

These resources would be expensive to duplicate, so they are operated in a "user facility" mode, and mechanisms have been established to provide access to users from across the country. While a large number of these facilities are located at Idaho National Laboratory, some are located at other national laboratories, industrial laboratories, and universities across the country.

These facilities make possible the advancement of fuels and structural materials for nuclear systems, provide data that permit confidence in the long-term operation of nuclear systems, enable reduction in risk, and keep the U.S. on the cutting edge of nuclear science and physics. In the maturation of concepts, test reactors are essential for fundamental studies, acquiring data, and testing off-normal conditions. If prototypic conditions are met, the basic physics understanding of particular phenomena can be studied in systematic ways and computer models can be validated. In these cases, test reactors are used to gain fuel qualification data and reduce the uncertainty associated with reactor concepts.

Beyond facilities and databases, the people who lead and execute research programs are critical to the nation's nuclear R&D capability, and the U.S. funds scholarship and fellowship programs to continually reinvigorate the nation's R&D workforce. Similarly, the trades programs that produce qualified technicians contribute to maintaining national capability. These programs are critical to keeping the pipeline vibrant.

Currently, the DOE-NE programs that support this tier include Idaho Facilities Management, Idaho Sitewide Safeguards and Security, Radiological Facilities Management, the Versatile Test Reactor project, and the Integrated University Program. This tier requires sustained funding because it supports a test bed for the existing fleet, for developing new concepts, and for supporting the U.S. Navy fleet.

Innovation

Includes support for the U.S. research community to propose and test high-risk, high-reward ideas through a large number of smaller funded projects. This innovation takes place at universities, national laboratories, and industrial laboratories.

The examination of new ideas in basic science and applications is both a mechanism and an opportunity for revitalization in any technology field. For nuclear energy, this could include advances in technology areas such as advanced manufacturing, artificial intelligence, high-performance computing, sensors and data, autonomous operation, construction techniques, and novel fuels and materials. Research into the economics and societal acceptance of nuclear technology—paired with effective communication about, for example, the potential advantages of microreactors and integrated energy systems—could incentivize new deployment opportunities. This tier also funds work to improve the abilities of the national facilities funded under the capability tier. For example, developing new detectors for the TREAT reactor to allow for more precise experimental results is one way that innovation can improve capabilities.

As noted in Figure 4.1, a large portion of university work is in the innovation tier, where basic discovery and fundamental science is the focus. Some work at the national laboratories also fits in the innovation tier.

Currently, the DOE-NE programs that support this tier include Nuclear Energy Enabling Technologies (NEET), Reactor Concepts RD&D, Fuel Cycle Research & Development, and NSUF. Fundamental science research conducted through Office of Science programs are important incubators for ideas proposed and tested in DOE-NE programs. This tier requires sustained funding to ensure future generations of technology will be ready to succeed those currently being deployed.

Development

Provides support for the U.S. research community to rapidly develop promising concepts in support of commercialization. The research performed in this tier evolves from the innovation tier and has less risk and greater promise. This development takes place at universities, national laboratories, and industrial laboratories.

This tier supports research that may need to take place over long periods of time to maintain important national databases, rapidly move good ideas toward commercialization, provide a stream of resources, and establish safety and safeguards practices for deployed nuclear systems. This tier is often described as applied science and engineering. This can include providing the data necessary to allow new fuels and materials to be used in commercial practice; building and refining databases, such as nuclear cross sections, used by reactor designers; and giving system operators confidence in their reliability over the lifetime of the technology. The GAIN program is a mechanism for industry to access to national capability to support their development.

Currently, the DOE-NE programs that support this tier include NEET, Reactor Concepts RD&D, Fuel Cycle Research & Development, and NSUF. This tier requires sustained funding because it supports testing for the existing fleet, for developing new concepts, and for supporting the U.S. Navy fleet.

It is important to recognize that in developing a new reactor concept, there is a continuous interplay between the innovation and development tiers as ideas are refined, rejected, or optimized.

Demonstration

Provides support, most often in cost share with an industry-leading developer, to demonstrate promising concepts as they approach commercialization.

In developing a new reactor, integral testing is typically necessary. In many cases, demonstration reactors are a necessary step for validating the entire reactor concept. This ensures the overall operation of the fuel-coolant combinations at the temperature, pressure, and neutron flux for a particular reactor design. At this step in the maturation of a reactor, industry takes a leading role in proposing the nuclear reactors that are funded. The government role is in supporting demonstrations as a first step in commercial viability, answering first-of-a-kind regulatory questions, and providing a platform for identifying opportunities for cost reduction in subsequent versions of the technology.

The DOE has made good strides in developing a funding pipeline in the ARDP. In addition, this tier includes funding for the National Reactor Innovation Center, which is facilitating industry efforts to field first-of-a-kind advanced reactor demonstrations.

Deployment

Provides early market support for concepts that are being deployed as a means of establishing the technology and providing a platform for industry-led cost reductions.

The federal government has several mechanisms to help emerging technologies get to market. These include production tax credits, power purchase agreements, tax incentives, clean energy portfolio standards, and loan guarantees. These mechanisms have been extremely successful in reducing costs for wind and solar technology. As nuclear technology products move beyond demonstrations, these deployment programs will help ensure they become established components of a clean energy system. Support for the establishment of reliable supplies of next-generation fuel, including a commercial supply of high-assay, low-enriched uranium (HALEU), are also critical to the deployment of advanced reactors.

5 Recommendations in Context

The ANS Task Force recommends an increase of about 95 percent in annual appropriations funding for nuclear RD&D by Fiscal Year 2030, compared to FY 2021 enacted levels. Relatively consistent funding beginning in FY 2029 will be necessary to field a new generation of nuclear technologies for commercial deployment in the 2030s, when many current reactors will be retiring.

ANS Task Force members and staff undertook a sustained effort to identify a set of core programs that are critical to the development and deployment of advanced nuclear fission technologies in the 2030 timeframe. These core programs reside primarily within the DOE's Office of Nuclear Energy, though support also comes through the DOE's Office of Science, the NNSA, and the NRC. Activities included detailed reviews of authorizing and appropriations legislation, agency budget justifications, and interviews with a broad cross section of the nuclear technology and policymaking community.

The Task Force then estimated the funding needed by 2030 to ensure that the U.S. can field a new generation of advanced technologies for commercial deployment at scale in the 2030s. Some of these core programs also support scientific missions that are not directly related to nuclear energy production, but nonetheless make important contributions to the effort we envision. Finally, these programs were grouped into four funding tiers:

Fundamental R&D and Science

Programs in this funding tier sustain research and development activities primarily at universities and national laboratories that are not specifically connected to a particular reactor design; provide radioactive and stable isotopes and other materials and infrastructure needed for such research; and support scholarships, fellowships, young faculty awards, and other funding essential to maintaining a robust pipeline of skilled, qualified nuclear engineers and scientists.

The Fundamental R&D and Science funding tier includes the following program areas: University Nuclear Leadership Program (UNLP), Integrated University Program (IUP), Joint Modeling and Simulation Program (NEAMS), High Flux Isotope Reactor (HFIR), Research

Reactor Infrastructure, Isotope R&D and Production, Front-End Fuel Cycle R&D, Cross-cutting and Enabling Technology R&D, and Fuel Cycle and Waste Management R&D. Nuclear Energy University Programs (NEUP) are also in the Fundamental R&D and Science tier, but are subject to change as a percentage of the total DOE-NE R&D budget and have not been included in the Task Force funding recommendations.

Enabling Science and Technology

This funding tier is focused on science and technology activities to move from bench to engineering scale, reduce uncertainties, and advance complex components such as advanced fuels. These activities are necessary for constructive engagement with commercial developers, and for establishing the viability of concepts to attract investors and customers.

The Enabling Science and Technology funding tier includes the following programs: Lab Operations and Infrastructure, Gateway for Accelerated Innovation in Nuclear (GAIN), Current Fleet Sustainability R&D, and Advanced Fuels.

Nuclear and Irradiation Facilities

This funding tier includes operations, upgrades, and construction for existing and proposed irradiation facilities that have a major role in testing specific components and systems of advanced reactor designs. It also includes necessary indirect costs associated with maintaining the laboratory infrastructure required for experiments.

The Nuclear and Irradiation Facilities funding tier includes the Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), the Versatile Test Reactor (VTR), and Future Test Reactor Upgrades. The tier also includes Safeguards and Security.

Demonstrations

This funding tier includes support for commercial entities through a series of competitively selected cooperative agreements that require a cost-share contribution to receive federal funding. These funding awards enable design, engineering, testing, licensing, and construction activities of a first-of-a-kind prototype or demonstration units.

The Demonstrations funding tier includes the following program areas: Early-Stage R&D for Advanced Reactor Designs (ARC-20), Advanced Reactor Demonstration Program (ARDP) Risk Reduction for Future Demonstrations, four full-scale demonstrations to be conducted under ARDP and the expected future ARDP 2.0, and Advanced Small Modular Reactor RD&D. Also included is the National Reactor Innovation Center (NRIC), an organization formed to facilitate use of national resources by nonfederal entities, and funding for regulatory development.

Note that some current funding lines encompass activities that could be considered applicable to more than one of the phases of the innovation pipeline described previously. However, the Task Force chose not to separate them, and instead classified them into funding tiers based on the principal thrust of the funding line.

Likewise, the Task Force did not specify advanced reactor deployment funding, such as investment and production tax credits, loan guarantees, and other incentives to construct and operate new nuclear plants. While support of this kind is recommended, and is essential to the commercial scale-up of advanced reactors, the Task Force determined that the selection of appropriate funding mechanisms was outside its realm of expertise.

Also outside the scope of the report are fusion and space nuclear power and propulsion. Originally the Task Force considered inclusion, but ultimately determined that its members did not have sufficient budgetary information available to make reliable, informed projections of outyear spending. The Task Force members encourage the leadership of ANS to consider addressing these issues in separate efforts.

Funding recommendations

Overall, the Task Force finds that the activities needed to field a new generation of nuclear technologies in the 2030 time frame would require a roughly 95 percent increase in annual appropriations funding levels for core nuclear RD&D activities between FY 2021 and FY 2030.

In total, this funding profile would result in approximately $10.3 billion in additional discretionary spending between now and FY 2030, when compared to FY 2021 levels. The major funding increases proposed are focused on three key outcomes already authorized by Congress with bipartisan support:

- Full funding for the first two demonstrations under the Advanced Reactor Demonstration Program (ARDP), planned for completion by 2027, and for a second round of demonstrations of designs expected to mature from the current ARDP Risk Reduction for Future Demonstrations award recipients. These would be funded for demonstration under a future "ARDP 2.0" starting in 2028. Finally, our recommendations also include fully funding early R&D concepts through the ARDP Risk Reduction and Advanced Reactor Concepts (ARC-20) programs.
- Construction of the VTR by 2030 to provide a versatile fast-neutron source to test and qualify advanced reactor technologies and materials, and build-out of the National Reactor Innovation Center for accelerated testing and demonstrations.
- Construction of an advanced light-water reactor (the UAMPS/NuScale Carbon Free Power Project) by 2029 to capitalize on past investments for the reactor closest to market.
- The Task Force also recommends, as a baseline, modest increases for existing programs which support essential research, development, and infrastructure. Highlights include:
- Maintaining the country's essential nuclear science and engineering infrastructure at our national laboratories and universities.
- The testing and development of advanced nuclear fuels for existing and advanced reactors.
- Operational improvements of the existing fleet of nuclear power plants through the Light Water Reactor Sustainability program.
- Improved economics for nuclear construction, operations, and innovations.
- Domestic production of therapeutic radioisotopes and radiopharmaceuticals to detect and combat cancer and other diseases.

The Task Force also notes that additional funding would be valuable to catalyze the deployment of an advanced reactor fleet at levels required to reach the decarbonization goals set by the Biden Administration and reestablish the U.S. as a nuclear technology exporter. Additional funding could offset high regulatory costs for advanced reactor licenses, jumpstart the production of hydrogen and other zero-carbon fuels with advanced reactors, and deploy new nuclear manufacturing and supply chain capabilities in the U.S.

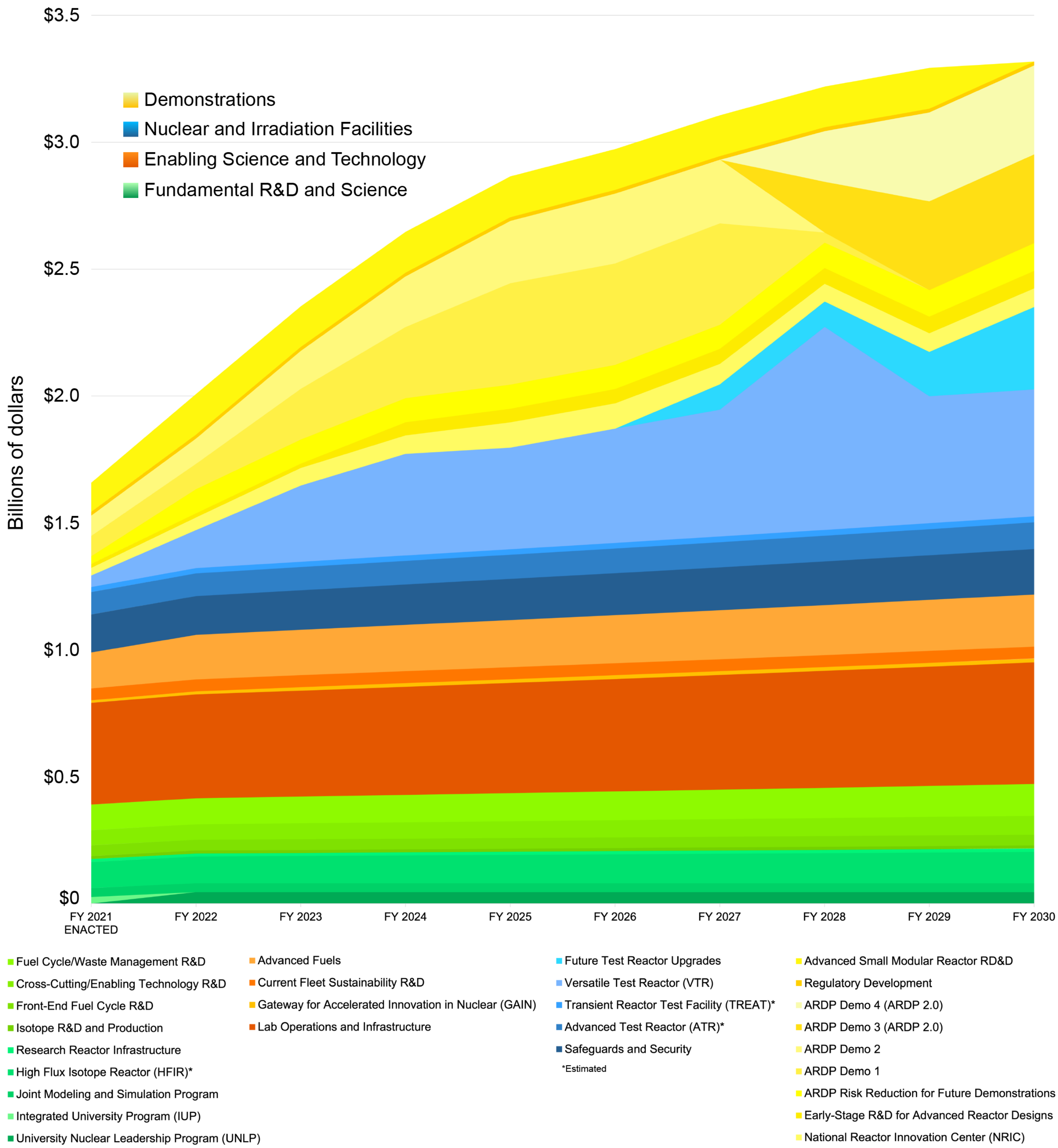


Figure 5.1. Recommended nuclear R&D funding (FY2021–FY2030). Programs have been stacked within four categories—**Fundamental R&D and Science**, **Enabling Science and Technology**, **Nuclear and Irradiation Facilities**, and **Demonstrations**—according to their scope and time frame. For example, fundamental programs that require steady funding and provide consistent support to multiple programs or end-users are placed below the more variable programs that they support, and near-term programs appear below the longer-term programs that will succeed them. Some funding lines, such as the VTR, are assigned to a single project, while other funding lines, such as Future Test Reactor Upgrades, represent projected costs to maintain or replace capabilities within a category and can potentially be applied to multiple facilities or programs.

Putting the costs in context

The recommended federal nuclear R&D investment may seem large compared to current appropriations, but it is a small fraction of the total cost of mitigating climate change.

- In comparison to the costs of **President Biden's $1.7 trillion climate plan**, the requested additional nuclear R&D support of $10.3 billion over nine years is approximately 0.6 percent of the administration's 10-year strategy.[53]
- In context of one year's worth of **current federal energy R&D spending**, the requested annual additional support for nuclear energy R&D is 13 percent of the $8.79 billion in total DOE energy R&D funding for enacted FY 2020, when averaged over nine years.[54]
- The requested additional nuclear R&D amounts to **less than two years of renewable energy subsidies** and tax incentives—with production tax credits for wind energy alone costing an estimated $9.2 billion in tax expenditures for 2018 and 2019.[55]
- In the context of **federal programs** that require similar long-term R&D support, the requested additional support of $10.3 billion over 10 years is consistent in scale. For example, NASA space exploration support has been sustained for 50 years, and NASA's Deep Space Exploration System budget is sustained at about $5 billion annually.[56]
- In the context of **past support for nuclear R&D**, the requested R&D is similar to nuclear fission R&D in 1977–1982, when $4 billion to $5 billion was allocated to nuclear energy annually.[57]
- According to the Environmental Protection Agency, the **saved social cost of carbon** from current nuclear energy production in U.S. is more than $20 billion annually.[58]

Conclusion

The ANS Task Force offers its recommendations to the nuclear policymaking community as Congress and the Administration consider options for expanding U.S. zero-carbon generating capacity to meet long-term decarbonization goals and provide a secure energy future for all Americans.

Preparing the United States to deploy advanced nuclear technologies by 2030 will require a significant expansion in this decade of federal R&D investments coordinated by the Department of Energy's Office of Nuclear Energy. Private investment in advanced nuclear technologies signals a level of market and technological readiness that can be accelerated by increased federal R&D support for America's largest carbon-free energy resource—and also accelerate a successful and rapid decarbonization and electrification of the U.S. economy.

The *ANS Task Force on Public Investment in Nuclear Research and Development* recommends approximately $10.3 billion in additional discretionary spending over nine years, from Fiscal Year 2022 to FY 2030, when compared to FY 2021 levels. The Task Force also recommends, as a baseline, modest increases for existing programs which support essential research, development, and infrastructure.

The major funding increases proposed are focused on three key outcomes:

- Full funding for the first advanced reactor demonstrations under the Advanced Reactor Demonstration Program (ARDP), followed by funding under a future "ARDP 2.0" to continue the pipeline and fund the next demonstrations, expected to mature from the current ARDP Risk Reduction award. Full funding of early R&D concepts through the ARDP Risk Reduction and Advanced Reactor Concepts (ARC-20) programs is also necessary to adequately nurture innovative concepts and maintain a robust pipeline for future commercial deployments.

- Construction of the VTR by 2030 to provide a versatile fast-neutron source to test and qualify advanced reactor technologies and materials, and a build-out of the National Reactor Innovation Center for accelerated testing and demonstrations.
- Construction of an advanced light-water reactor by 2029 to capitalize on past investments for the reactor closest to market.

To effectively answer the national imperatives of clean energy, economic growth, and national security, the U.S. must be equipped to sustain a strong nuclear energy enterprise both domestically and internationally. This need constitutes a new imperative, a nuclear sustainability imperative. Without nuclear sustainability, progress on our national imperatives will be impeded and the U.S. will not maintain a leadership role in the international nuclear community.

Supplied with adequate appropriations, and with a nascent commitment to development programs measured by milestones, the DOE's Office of Nuclear Energy is advised to implement a pipeline approach to managing nuclear R&D programs. An innovation pipeline will ensure that the U.S. gets full value for its investment as every concept is evaluated on its merits, yielding a steady output of technological advancements for decades to come.

Americans who are working hard every day to develop the technological solutions to global climate change are eager for increased nuclear R&D funding and a sustained commitment from the federal government. Now is the time to invest to secure America's clean energy future.

References

1. www.ipcc.ch/sr15
2. energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/
3. www.ethree.com/e3-examines-role-of-nuclear-power-in-a-deeply-decarbonized-pacific-northwest
4. www.cell.com/joule/fulltext/S2542-4351(18)30386-6
5. sepapower.org/utility-transformation-challenge/utility-carbon-reduction-tracker/
6. www.duke-energy.com/_/media/pdfs/our-company/climate-report-2020.pdf?la=en
7. nei.org/CorporateSite/media/filefolder/resources/fact-sheets/nei-nuclear-by-the-numbers-092520-final.pdf
8. www.eia.gov/todayinenergy/detail.php?id=41433
9. Bloomberg News, "China's Top Climate Scientists Plan Road Map to 2060 Goal," September 28, 2020. www.bloombergquint.com/onweb/china-s-top-climate-scientists-lay-out-road-map-to-hit-2060-goal
10. www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
11. www.lucidcatalyst.com/hydrogen-report
12. www.nrel.gov/docs/fy17osti/66763.pdf
13. S. Julio Friedmann, Zhiyuan Fan, and Ke Tang, "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," Center on Global Energy Policy, October 2019.
14. 200416_Nakano_NuclearEnergy_UPDATED FINAL.pdf (csis-website-prod.s3.amazonaws.com)
15. csis-website-prod.s3.amazonaws.com/s3fs-public/publication/200416_Nakano_NuclearEnergy_UPDATED%20 FINAL.pdf?heOTjmYgA_5HxCUbVIZ2PGedzzQNg24v
16. www.reuters.com/article/us-china-nuclearpower-idUSKCN1TL0HZ
17. csis-website-prod.s3.amazonaws.com/s3fs-public/publication/200416_Nakano_NuclearEnergy_UPDATED%20 FINAL.pdf?heOTjmYgA_5HxCUbVIZ2PGedzzQNg24v
18. rosatom.ru/upload/iblock/0c1/0c106b40899f365fd8c2a6be935b092b.pdf
19. https://davidgattieblog.files.wordpress.com/2020/07/gattie-massey-ssq-2020-twenty-first-century-us-nuclear-power-a-national-security-imperative.pdf
20. Restoring America's Competitive Nuclear Energy Advantage | Department of Energy
21. Matt Bowen, "Why the United States Should Remain Engaged on Nuclear Power: Geopolitical and National Security Considerations," Columbia University SIPA Center on Global Energy Policy, 2020.
22. www.csis.org/analysis/changing-geopolitics-nuclear-energy-look-united-states-russia-and-china
23. brattlefiles.blob.core.windows.net/files/5921_the_nuclear_industry's_contribution_to_the_u.s._economy.pdf
24. www.atlanticcouncil.org/in-depth-research-reports/issue-brief/the-value-of-the-us-nuclear-power-complex-to-us-national-security/#conclusion
25. Nuclear Power Pays: Assessing the Trends in Electric Power Generation Employment and Wages, Oxford Economics www.oxfordeconomics.com/recent-releases/nuclear-power-pays-assessing-the-trends-in-electric-power-generation-employment-and-wages
26. e2.org/wp-content/uploads/2020/10/Clean-Jobs-Better-Jobs.-October-2020.-E2-ACORE-CELI.pdf, p13
27. *2020 U.S. Energy and Employment Report*, p. 108, 113 and 119 www.usenergyjobs.org
28. www.payscale.com/research/US/Job=Solar_Energy_System_Installer/Hourly_Rate

29. 2020 U.S. Energy and Employment Report (USEER) (usenergyjobs.org)
30. decommissioningcollaborative.org/wp-content/uploads/2020/10/Socioeconomic-Impacts-from-Nuclear-Power-Plant-Closure-and-Decommissioning-15-October-2020-Final.pdf
31. www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/UxC-NEI-(IPCC-2050-Nuclear-Market-Analysis-PUBLIC)-2020-07-01.pdf
32. Global Nuclear Market Assessment Based on IPCC Global Warming of 1.5° C Report (nei.org)
33. Mapping the Global Market for Advanced Nuclear – Third Way
34. www.energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-demonstration-program
35. Nuclear Innovation Alliance, "Leading on SMRs," 2017.
36. Ingersoll et al, "Can Nuclear Power and Renewables be Friends?" Proceedings of ICAPP 2015, May 3-6, 2015.
37. www.terrapower.com/exploring-the-natrium-energy-storage-system/
38. www.nuclearalternativeproject.org
39. clearpath.org/our-take/one-of-worlds-largest-energy-consumers-embracing-advanced-nuclear
40. beta.sam.gov/opp/c43c35ee3c794aa8aa09a30dc0ec8ded/view
41. www.fusionindustryassociation.org/members
42. https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/DRAFT_Fusion_and_Plasmas_Report_120420.pdf
43. USDRIVE Grid Integration Tech Team and Integrated Systems Analysis Tech Team Summary Report on EVs at Scale and the U.S. Electric Power System November 2019
44. www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a
45. www.lucidcatalyst.com/arpa-e-report-nuclear-costs
46. www.lucidcatalyst.com/hydrogen-report
47. ies.inl.gov/SitePages/Home.aspx
48. www.ans.org/file/1245/Progress+on+Nuclear+Waste+Management.pdf
49. www.thirdway.org/graphic/2019-advanced-nuclear-map
50. www.thirdway.org/report/a-step-by-step-guide-to-nuclear-innovation-policy
51. www.nuclearinnovationalliance.org/index.php/search-spacex-nuclear-energy
52. www.nasa.gov/content/cots-final-report
53. finance.yahoo.com/news/see-joe-biden-plans-shocking-010003390.html
54. www2.itif.org/2020-energy-innovation-funding-full-report.pdf
55. fas.org/sgp/crs/misc/R43453.pdf
56. www.nasa.gov/sites/default/files/atoms/files/fy2021_mission_fact_sheets.pdf
57. www.iea.org/reports/energy-technology-rdd-budgets-2020
58. 19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

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