ADVANCED NUCLEAR PROCESS HEAT FOR INDUSTRIAL DECARBONIZATION

C2ES CLIMATE INNOVATION 2050

by

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Achieving net-zero emissions will require large-scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we lay out in Getting to Zero: A U.S. Climate Agenda,[1] reaching net zero will require large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of "Closer Look" briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs explore policy implications and outline key steps needed to reach net zero by mid-century.

EXECUTIVE SUMMARY

The industrial sector is responsible for about 30 percent of U.S. greenhouse gas emissions. Many of these emissions come from the heat needed for industrial processes in subsectors such as steel, concrete, chemicals, and glass production, since these subsectors typically rely on low-cost, high-emitting fossil fuels as their primary source for uninterrupted thermal energy. To reduce dependence on fossil fuels and achieve decarbonization targets, non-emitting heat sources that meet the unique challenges of powering the industrial sector must be further developed and deployed in the near future. Advanced nuclear technologies could play both direct and indirect roles in providing such heat, and their inherent safety, siting flexibility, modularity, and small land footprint could enable cost-effective deployment at a wide range of locations.[2]

Existing nuclear power plants and new advanced nuclear reactors could directly provide heat at a range of temperatures and at the high capacity factors (i.e., almost always on availability) needed by many industrial users, which means nuclear reactors could effectively replace much of the heat currently generated by fossil fuels. In addition, electricity from advanced reactors could power electrified heat options (e.g., industrial heat pumps) and production of zero-carbon hydrogen, as well as carbon capture technology that could further decarbonize industry.

Accelerating the deployment of advanced nuclear reactors faces a range of challenges, including cost concerns, regulatory delays, supply chain risks, inadequate workforce, lack of a long-term plan for storage of nuclear waste, non-proliferation concerns, and opposition from some states and communities.[3] Recent policy actions in Congress, the U.S. Department of Energy (DOE), and the Nuclear Regulatory Commission (NRC) have sought to mitigate some of these challenges, including through robust funding for nuclear deployments, support for boosting domestic nuclear fuel production, and development of new regulatory review pathways.

More is needed, however, to drive technological advancements and widespread deployment. Necessary policies include:

- **Additional financial and technical support:** Additional public dollars for research, development, and deployment of advanced nuclear reactor technologies (inclusive of fuel and other supplies) and for workforce development, along with expanded technical support for industrial facilities looking to adopt advanced nuclear technologies, could help spur further private investment and develop an advanced nuclear market in the United States.
- **NRC action and support:** Efforts to finalize new, more efficient licensing procedures for advanced nuclear reactors must continue, and the NRC needs additional staff and resources to handle the anticipated volume of applications for new reactors in the near future.
- **Carbon pricing:** Market-based solutions to incentivize emissions reductions would encourage and improve the cost-competitiveness of industrial decarbonization efforts. A price on greenhouse gas emissions would reflect the true cost of emitting carbon (e.g., costs to society such as damage from more extreme weather); with a market-based incentive, businesses and consumers will take steps to decarbonize, including deploying innovative advanced nuclear technologies and fuels, to avoid increased costs and remain economically viable.

Industrial decarbonization is key to the United States achieving its 2050 net-zero climate target. Advanced nuclear technologies, if adequately supported and developed, could complement an array of other clean energy technologies in making such decarbonization a reality while supporting increased U.S. energy security and economic growth.

BOX 1: Key Takeaways

- Nuclear power is one of the few technologies that can economically and technologically meet the thermal needs of industrial process heat applications up to 950 degrees C (1,742 degrees F).
- Retrofitting facilities (e.g., manufacturing, universities, hospitals) currently utilizing natural gas-fired combined heat and power systems would reduce U.S. annual carbon dioxide emissions by at least 75 million metric tons per year.
- Small modular reactors can scale to fit a wide range of industrial needs; given their modularity and geographic independence, they will be capable of supplying safe, reliable thermal energy and electricity.
- Early projects, such as the X-energy and Dow partnership, have encouraged other companies to consider nuclear technology for their own facility needs.
- A thriving hydrogen market could help drive demand for nuclear combined heat and power applications, as production of hydrogen from nuclear plants becomes more cost-effective and usable due to increased hydrogen infrastructure.
- Continued public investments in development, deployment, and licensing of nuclear reactor technologies and fuel supply is essential to encourage private investments.
- Highly-scalable, zero-emission technologies like nuclear energy will be necessary to meet growing demand from electrification, artificial intelligence, and other new sources of electricity and heating demand. Encouraging advanced nuclear for process heat in these and similar applications could help (e.g., develop, scale, reduce costs) the technology, making nuclear more accessible for electricity generation.

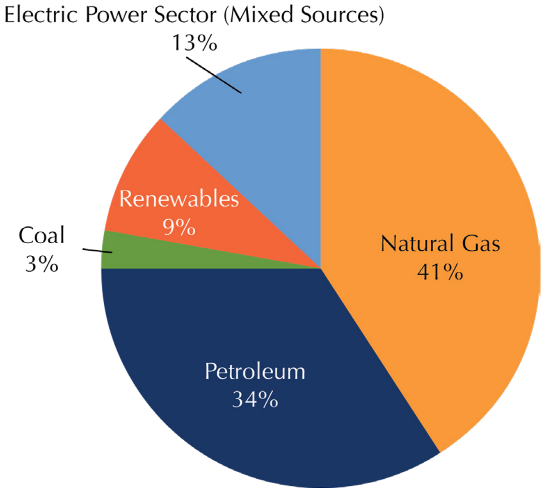
INTRODUCTION

THE U.S. INDUSTRIAL SECTOR

The U.S. industrial sector manufactures essential products, from building materials such as steel and concrete to everyday necessities such as chemicals and food. The industrial sector is considered among the more challenging sectors to decarbonize, primarily because it relies on not just electricity but also on heat in diverse subsector processes. In addition, industrial facilities often sell products at low-commodity prices and operate on relatively tight profit margins; thus, large-scale decarbonization technologies that require high capital cost investments with long payback periods—like advanced nuclear—are challenging for industrial facilities to adopt without harming their economic viability.[4]

Currently, fossil fuels are used onsite for the majority of industrial energy demands in the United States, as shown in Figure 1. The range of onsite and remote energy sources breaks down roughly as follows: 41 percent from natural gas, 34 percent from petroleum, 3 percent from coal, 9 percent from renewables, and 13 percent from mixed sources through the electric power sector.[5] In terms of direct emissions (i.e., excluding electricity received from the power sector via transmission and distribution lines), the industrial sector is responsible for nearly a quarter of U.S. emissions, and that percentage has been steadily increasing since 2010. Counting the externally produced electricity the sector consumes, the percentage rises to around 30 percent of U.S. emissions.[6] To minimize U.S. emissions, it is imperative to rapidly decarbonize the industrial sector.[7]

FIGURE 1: Industrial energy fuel source



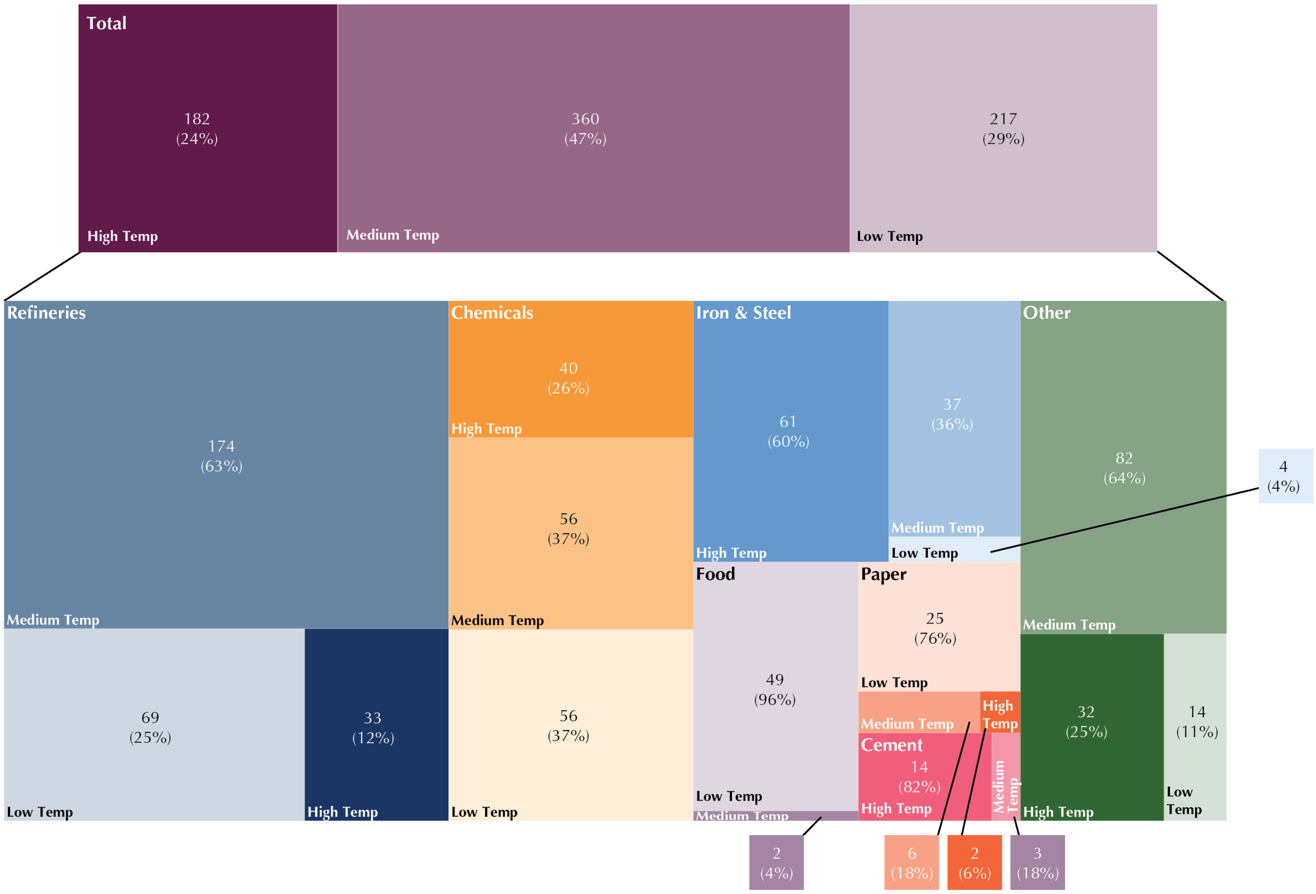
Thermal energy comprises two-thirds of all energy demand in the industrial sector, representing a huge emissions reduction opportunity.[8] Low- and medium-temperature heat (i.e., under 500 degrees C [932 degrees F]) account for 76 percent of total industrial thermal demand in the United States, as shown in Figure 2.[9] Emissions from low- and medium-temperature heat applications are generally easier to abate, as a broader range of clean thermal energy technologies can provide such heat. In addition to current and advanced nuclear reactors, options for low- and medium-temperature heat include solar thermal (which can reach 700 degrees C [1,292 degrees F]) and industrial electric heat pumps (which can reach 130 degrees C [266 degrees F] but have future potential to reach 200 degrees C [392 degrees F]).[10] Some electrification technologies can attain very high temperatures, such as electric arc furnaces (which can reach 1,800 degrees C), though they have substantial electricity demands.[11] The remaining 24 percent of industrial thermal demand—currently met primarily through the combustion of fossil fuels—needs higher-heat clean technology solutions such as hydrogen and advanced nuclear reactors.

NUCLEAR TECHNOLOGIES

Although nuclear energy has the potential to provide a relatively unique solution set for decarbonizing industrial thermal demand, nuclear is generally thought of and utilized as a source of zero-carbon electricity. This is understandable: the United States' 94 nuclear reactors—found in more than half of U.S. states—accounted for 19 percent of U.S. electricity generation in 2022.[12] Worldwide, 440 nuclear reactors produce 10 percent of all global electricity and 26 percent of zero-carbon power.[13]

Nuclear reactors produce no greenhouse gas emissions during their operation and are among the lowest emitters on a lifecycle basis of all power generation technologies.[14] Other benefits of nuclear power is its geographical independence, whereas some other clean energy technologies, such as solar and wind, are not. It also has a relatively small land use footprint, requiring about 1.3 square miles per 1,000 megawatts (MW) of installed capacity—31 times less land than required by solar photovoltaic (PV) arrays and 173 times less than wind turbine facilities.[15]

FIGURE 2: Industrial Thermal Emissions by Temperature Range



Distribution of total U.S. industrial thermal emissions across low-, medium-, and high-heat processes (less than 130 degrees C, 130–500 degrees C, and more than 500 degrees C, respectively), as well as division by industrial sector. Units are in million tons of carbon dioxide equivalents.

Source: Renewable Thermal Collaborative, The Renewable Thermal Vision: Finding a Path Forward for Decarbonizing Thermal Energy in the U.S. Industrial Sector (Arlington, VA: RTC, 2022), https://www.renewablethermal.org/vision

Nuclear reactors create heat to generate power. Commercial nuclear reactors function by harnessing the heat energy released from the controlled splitting (fission) of atoms to produce steam, which drives turbines to produce electricity. The pressurized water reactor (PWR) is the most common reactor design, accounting for almost 70 percent of reactors globally.[16] The PWR design utilizes two water circuits: a pressurized primary cooling water circuit to transfer heat from the nuclear fuel and a distinct, secondary water circuit where water boils under lower pressure to generate steam. The steam in the secondary circuit is used to drive a turbine to produce electricity. Comparably, a boiling water reactor (BWR) generates steam in its primary circuit above the reactor core under similar conditions. PWRs and BWRs are both types of light-water reactors. Pressurized heavy-water reactors (PHWR) use an isotopically different form of water called heavy water (water enriched in hydrogen atoms with an extra neutron) to moderate the reactor and can use naturally occurring uranium as fuel rather than the enriched uranium fuel used in other reactors.

Commercial fission reactors tend to be very large, but small modular reactors (SMRs) of various designs are currently under development and are likely to be deployed in the United States within the next decade. SMRs can be designed to fit a variety of different deployment scenarios due to their modularity, siting flexibility, safety features, reduced construction time, and lower costs.[17] The total energy output of these small reactors can be scaled up or down by adjusting the number of modules.[18] They can be deployed in remote or populated areas, particularly as their smaller site boundaries reduce the size of their emergency planning zones. Most SMRs are designed with a high level of passive and inherent safety mechanisms—for example, physical forces like convection or gravity—that enable safe operation and would shutdown the reactor in the event of a system malfunction. On the other hand, traditional reactor safety systems require operators to implement electrical or mechanical actions to cause a shutdown. Some SMRs use new types of fuels and are designed to operate for decades without refueling.[19] Additionally, SMRs can start up from a completely de-energized state without any energy input from the grid (black start functionality), making them potentially very useful resilience assets in locations with low grid reliability.[20]

The modularity of SMRs offers potential cost savings and faster implementation timelines (i.e., relative to much larger, legacy reactors) as many components can be fabricated in a factory and then shipped to the site for installation. This aspect of the design reduces the need for on-site preparation and construction, thereby reducing completion times and increasing economic viability. Additionally, modules may be deployed incrementally to match rising energy demand, minimizing upfront costs for projects.

Various SMR designs have recently received attention and progressed further along in the development and deployment process in the United States. There are over 80 SMRs in development; Table 1 represents some of the more advanced projects and details design features and federal support for these reactors.[21]

In addition to fission reactors, there have been recent breakthroughs in fusion technology as well, which generates heat by merging two atoms instead of splitting them. This technology, however, is less developed, and the use of fusion technology for energy production has not yet been demonstrated at a scientific or commercial scale.[22]

NUCLEAR PATHWAYS TO SUPPORT INDUSTRIAL HEAT DECARBONIZATION

Although nuclear is generally thought of in the context of zero-carbon electricity generation, there are two main pathways by which nuclear can support decarbonization of industrial heat: by providing that heat directly and by generating zero-carbon electricity to provide other decarbonization options (e.g., hydrogen; carbon capture use, and storage [CCUS]). As electricity demand rises in the United States, zero-carbon and energy-dense power such as nuclear must scale up to support the nation's clean energy transition and ensure energy security.[23]

DIRECT (VIA COMBINED HEAT AND POWER)

As noted earlier, heat is an intrinsic part of nuclear energy generation, but nuclear plants typically convert only about one-third of thermal energy to electricity, with the rest unutilized (i.e., going up into the air).[24] If sited in proximity to industrial facilities, nuclear combined heat and power (CHP) systems can be practically connected to (i.e., via relatively short piping) and utilize most of the remaining two-thirds to directly meet industrial thermal demands.

Existing nuclear power plants typically have high power outputs (around 1,000 MW of electricity production or 3,000 MW of thermal energy) and operate at lower temperatures (around 350 degrees C or lower). There are several examples where nuclear is currently being used for lower-temperature heat applications, such as water desalination and district heating. For instance, the Beznau nuclear plant in Switzerland supplies district heating, serving an 80-mile network of homes and industry in 11 towns. Finland aims to power much of its existing district heating systems with energy from its nuclear facilities.[25] Many other similar examples exist, mainly in Europe and Russia.[26]

New advanced reactor technologies under development have a variety of power outputs (from single megawatts to hundreds of megawatts of thermal energy) and higher operating temperatures (potentially up to 1000 degrees C in some designs). As noted earlier, they also have improved inherent safety and more flexible siting criteria that enable deployment at a wider range of locations.[27] These advanced nuclear reactors can supply the thermal energy needs of a broader set of industries, as shown in Figure 3. For instance, the temperature output of a High-Temperature Gas-Cooled Reactor (HTGR) can reach 950 degrees C (1,742 degrees C).[28] This means that this technology could satisfy the heat requirements of most high-emitting industrial processes, such as those in the chemical, petroleum refining, food and beverage, and pulp and paper sectors.[29] (The heat needed for glass

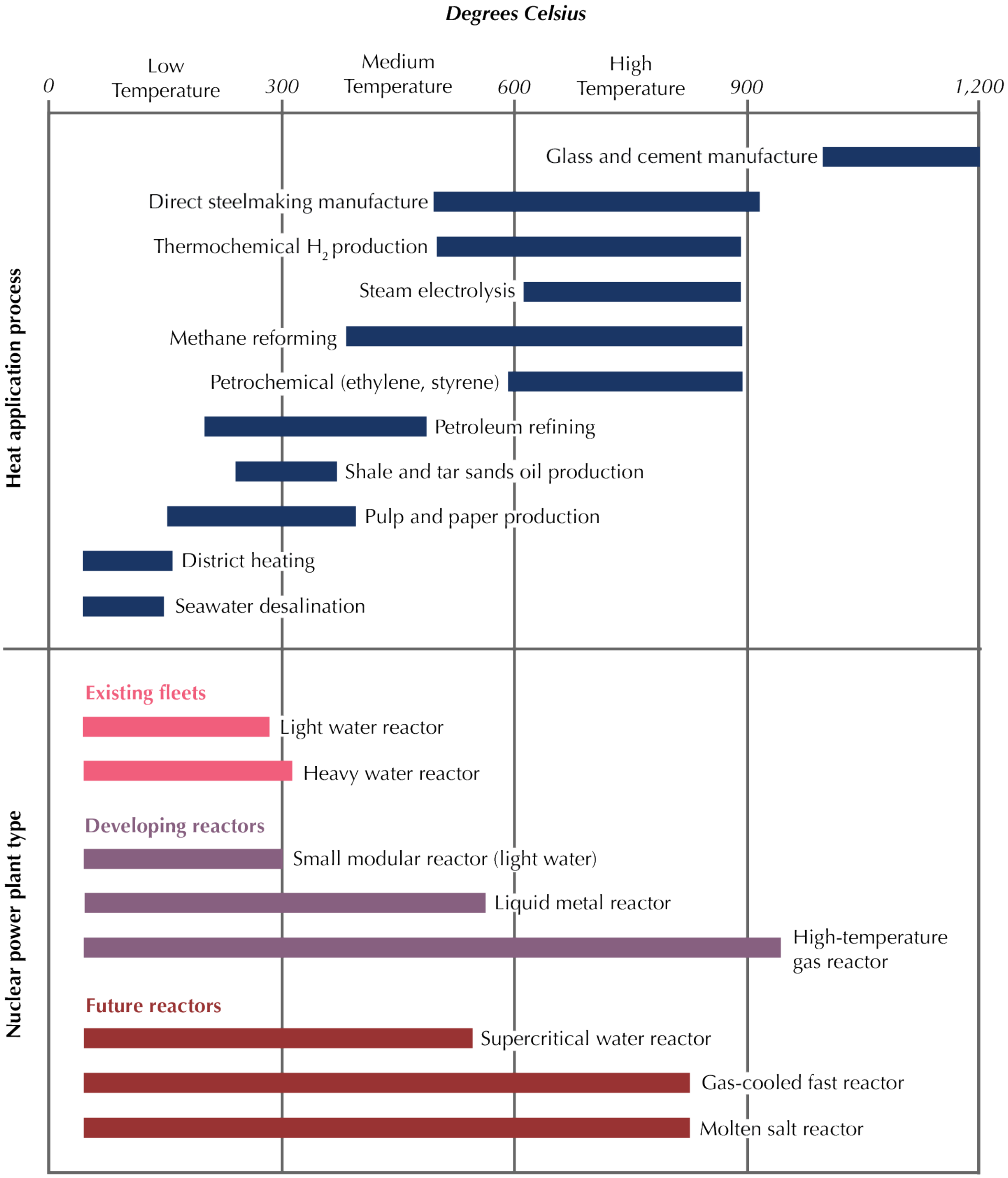
TABLE 1: Highlighted SMRs in Development

Name of Reactor	Reactor Type	Highlighted Design Features	Federal Support
*GE-Hitachi BWRX-300**	Boiling Water Reactor (BWR)	• Water-cooled, natural circulation SMR utilizing passive safety systems[1] • Is based on proven and licensed BWR technology	This design is based on BWR technology that was previously supported through DOE's Nuclear Power 2010 Program.[2]
NuScale VOYGR	Pressurized Water Reactor (PWR)	• Is based on proven pressurized water-cooled reactor technology • Is the first SMR to receive approval from the NRC[3]	DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative awarded a voucher to enable Oak Ridge National Laboratory to support the development of the NuScale reactor's heat augmentation system.[4]
*Oklo Aurora***	Fast Reactor	• Is able to use spent fuel from conventional nuclear reactors to produce power[5]	The design is being considered for a government award to power an Air Force base in Alaska.[6]
TerraPower Natrium	Sodium Fast Reactor (SFR)	• Utilizes fast-reactor fuel cycles that can more efficiently use nuclear fuels as compared with existing nuclear reactors • Integrates thermal storage capabilities to provide flexible clean energy at a competitive cost[7] • Is the only coal-to-nuclear project currently under development in the world[8]	TerraPower was selected by DOE in 2020 to receive almost $2 billion in cost-shared funding through the Advanced Reactor Demonstration Program (ARDP) to build the Natrium Demonstration Project in Wyoming.[9] The company received $8.5 million in funding from DOE through the Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS) Program in 2022 to research an experimental method for the recovery of uranium from spent nuclear fuel.[10]
Westinghouse AP300	Pressurized Water Reactor (PWR)	• Builds on the experience and supply chain developed from the company's larger AP1000, currently active in Georgia and abroad in China[11]	This design is based on Westinghouse's AP1000 design, which received about $12 billion in loan guarantees from DOE over several years.[12]
X-energy Xe-100	High-Temperature Gas-Cooled Reactor (HTGR)	• Uses proprietary tri-structural isotropic (TRISO) fuel and passive safety systems to enhance safety and produce extremely high-temperature heat • For at least the first plant, is designed to integrate with existing chemical production facilities as an industrial heat supplier	X-energy was selected by DOE in 2020 to receive $1.2 billion in federal cost-shared funding under the ARDP to develop and demonstrate an operational advanced nuclear reactor and fuel fabrication facility by 2030.[13]

*Poland, a country that derives 70 percent of electricity from coal, has approved two dozen BWRX-300 SMRs for construction at six locations.[14]

**Oklo has signed a letter of intent to provide 500 MW to Equinix to serve its data centers under a 20-year power purchase agreement (PPA).[15]

FIGURE 3: Industrial Heating Needs and Nuclear Plant Expected Heat Output



The range of industrial process heat applications and the heat outputs of existing, developing, and future reactors. Advanced nuclear designs like the HTGR can meet the thermal needs of most industries, and other designs are sufficient for low- and medium-temperature heat applications. Temperature scale is in degrees Celsius.

Source: "Nuclear Process Heat for Industry," World Nuclear Association, updated September 2021, https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry.aspx.

BOX 2: TRISO Fuel Pebbles

Unique to X-energy's SMRs is a tri-structural isotropic (TRISO) particle fuel embedded in a novel billiard ball-sized fuel element and designed to be safer than average fuel as it can withstand very high-temperature, worst-case scenario conditions without melting.[16] Within the TRISO fuel pebble are 18,000 TRISO particles, each containing a uranium kernel encased in three carbon layers; each pebble acts as its own containment vessel, reducing reliance on extensive containment structures and large safety margins.[17]

FIGURE 4: TRISO Fuel Pebble Diagram[18]

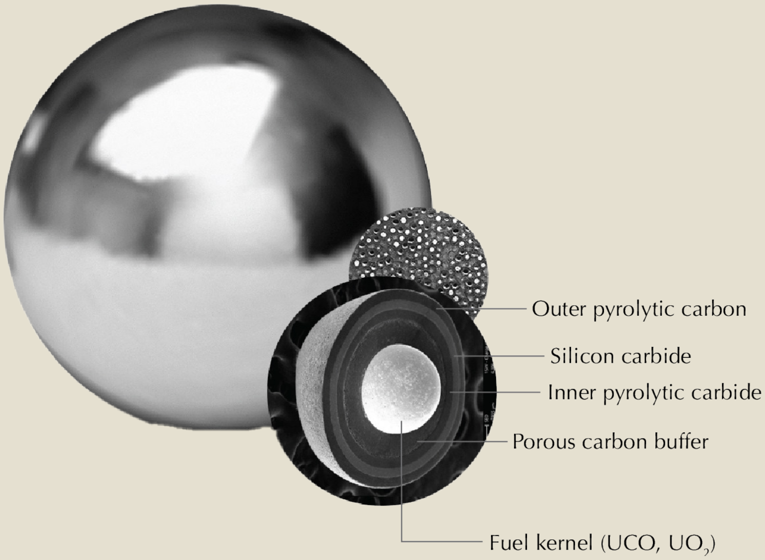


Image Courtesy of X-energy.

and concrete production, however, remains higher than nuclear plant designs are currently projected to be able to directly provide.)

There are already plans under development to use advanced nuclear CHP to meet the needs of industrial facilities. In May 2023, Dow, Inc. signed a joint development agreement with X-energy to deploy the first advanced SMRs at an industrial site: Dow's Seadrift manufacturing facility on the Gulf Coast, near Corpus Christi, Texas. The Seadrift facility manufactures over 4 billion pounds of material each year, including food packaging, footwear, wire and cable insulation, solar cell membranes, and medical packaging.[30] Dow and X-energy expect to begin construction in 2026 and complete the installation of one of the reactors by 2030. Four units of X-energy's Xe-100 HTGR will ultimately be built at the site. The units will be capable of generating 320 MW of electrical output and 565 degrees C (1,049 degrees F) steam, meeting the needs of the Seadrift site as existing fossil-fuel cogeneration assets approach retirement.[31] The melting temperature of plastic is typically below 300 degrees C (572 degrees F), well within the thermal capabilities of the X-energy reactor when using a combined heat and power (CHP) system.[32] The project is expected to reduce the facility's emissions by 440,000 metric tons (MT) of carbon dioxide equivalents each year, equal to the emissions from nearly 100,000 light-duty vehicles per year.[33] In addition, since CHP systems are typically designed and sized to fulfill the heating needs of an industrial facility, there is likely to be substantial excess zero-emission electricity generation, which with the proper policy instruments in place, may be sold to other grid customers, reducing the carbon intensity of power across Southern Texas.

Nuclear CHP systems could efficiently provide both the power and the heat that industrial facilities require, maximizing power plant efficiency relative to the capital invested while slashing emissions.[34] Retrofitting existing gas-fired CHP facilities (e.g., at manufacturing plants, universities, and hospitals) with advanced nuclear would reduce U.S. carbon dioxide emissions by at least 75 million MT per year (e.g., equivalent to taking more than 16 million passenger vehicles off the road each year) and have virtuous follow-on effects by helping to reduce the cost of future advanced nuclear deployments for power and other applications.[35]

Adding thermal energy storage to CHP systems would further enhance efficiency.[36] Nuclear reactors generate power continuously—when energy demand is low, excess thermal energy could be stored, creating a supply buffer for potential future demand spikes. The stored heat could also be used to generate electricity, filling gaps during the downtimes of variable renewable energy such as solar or wind, creating a diverse and reliable power supply. Molten salt-based storage, which is incorporated into the Natrium reactor under development by TerraPower and GE-Hitachi to boost potential power output, is one cost-competitive potential thermal storage option. The storage can increase the overall plant output from 345 MW to 500 MW for more than five hours, creating flexible redundancy without additional units.[37]

INDIRECT

Beyond directly providing heat for process heat applications, nuclear reactors could also indirectly decarbonize industrial thermal needs through the indirect use of the zero-carbon electricity and heat they generate. Using nuclear to produce clean hydrogen is a prime example.

As an energy carrier, hydrogen can store and transport energy produced from various energy sources in a usable form with high energy content. One of the benefits of hydrogen is that it can be stored in large quantities for long periods (i.e., indefinitely or seasonally).[38] When combusted, hydrogen can produce very high temperatures: up to 2,100 degrees C—high enough to meet the temperature demands of all industry sectors, including concrete and glass manufacturing.[39] Since it can reach such high temperatures, it can be a viable replacement for fossil-fuels across sectors.[40]

Although hydrogen emits no carbon dioxide when burned, its production can be carbon intensive, depending on its production pathway. Currently, 95 percent of hydrogen produced in the United States is made via carbon-intensive steam methane reforming—a process that uses natural gas as an input and power source. For such hydrogen to be a viable decarbonization option, this process must be supplemented with CCUS, which would give the resulting hydrogen a much smaller carbon footprint.

BOX 3: Industrial Clusters

Hydrogen and heat have something in common: localized usage is better. Both face barriers in being efficiently transported long distances: heat, because it dissipates quickly; hydrogen, because it requires specialized pipeline infrastructure to minimize leaks, which if not controlled would exacerbate global warming, i.e., hydrogen is an indirect greenhouse gas. That means industrial clusters could be prime locations for nuclear-provided heat or hydrogen. Industrial clusters are geographically linked facilities that share or exchange resources in ways that provide economic and energy efficiency benefits. These clusters are responsible for about 20 percent of European emissions and about 15 percent of U.S. emissions, creating great opportunities for emissions reductions through electrification, thermal optimization, concentrated hydrogen demand, and efficient CCUS.[19] Industrial clusters could benefit by using nearby advanced reactors as sources of heat or hydrogen, resulting in more efficient thermal optimization and lowered demand for high-emitting forms of heat.[20] Industrial clusters also serve to minimize investments for all facilities involved due to the ability to share cost burdens.[21]

Alternatively, zero-carbon hydrogen can be produced via electrolysis, wherein renewable or nuclear electricity powers an electrolyzer to split water into hydrogen and oxygen. High-temperature electrolysis is even more efficient at separating hydrogen and oxygen than conventional electrolysis. Yet another production pathway is thermochemical water splitting, which uses high heat to drive chemical reactions that produce hydrogen.

Nuclear plants generate constant power, meaning hydrogen made from nuclear energy has a high capacity factor relative to other production methods, and thereby lower costs per unit of electricity.[41] High-temperature heat and electricity generated from advanced nuclear reactors could be used to produce hydrogen through high-temperature steam electrolysis or by using the heat from the nuclear plant for thermochemical processes.[42] The high exit temperature of the HTGR's helium coolant (about 950 degrees C), for instance, means it could be very promising for hydrogen production. In theory, a nuclear reactor could directly meet the low- and medium-temperature heat demands of an industrial facility using its direct output heat, and could use low-carbon hydrogen created from the electricity and heat generated by the reactor to meet the higher thermal needs of sectors such as concrete.[43]

Potential indirect applications for nuclear energy for industrial decarbonization extend beyond hydrogen. Nuclear CHP could power CCUS technologies and perhaps direct air capture (DAC) systems, potentially resulting in carbon-neutral or carbon-negative industrial facilities.[44] This could be especially useful in industries (e.g., cement) that cannot completely eliminate emissions through fuel-switching due to process emissions unrelated to burning fuel. (The majority of emissions from cement production stem from the chemical reaction that occurs when limestone is heated.) Nuclear CHP could be a particularly good and cost-effective option for supporting DAC systems, which require both electricity and heat to remove carbon dioxide directly from the atmosphere. Recently, DOE awarded two projects—the Byron Generating Station in Byron, Illinois, operated by Constellation Energy, and the Joseph M. Farley plant in Colombia, Alabama, operated by Southern Company—$2.5 million each of cost-shared funding to demonstrate DAC at nuclear facilities.[45]

CHALLENGES TO SCALING THE TECHNOLOGY

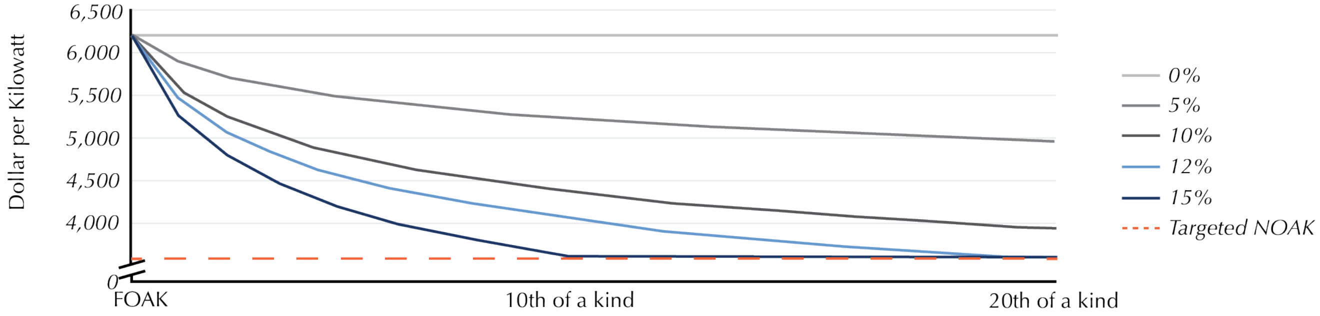
Scaling innovative nuclear technology is challenging. The high cost of development and deployment, inefficient licensing processes, limited availability of skilled workers, issues related to fuel sourcing, and myriad other challenges have all contributed to widespread uncertainty regarding commercializing advanced reactors.

COST

One of the biggest barriers to large-scale deployment of nuclear reactors is the capital cost involved in designing, siting, and building them. In traditional large nuclear projects, the final bill often runs over initial cost estimates by substantial margins.[46] Smaller SMR projects, however, should have more manageable costs. For one thing, many components of modular designs can be fabricated off-site before construction begins, which will decrease construction timelines and associated labor costs compared to conventional reactors.[47] Modularity also enables industrial customers to only purchase the number of units needed to produce their desired energy output, reducing overall capital expenditures. Some SMRs allow for additional reactor modules to be installed later, if demand increases.

Still, nuclear plants have high capital costs compared to other forms of clean energy (e.g., solar and wind) and to fossil fuels.[48] However, nuclear reactors have unique benefits, including high energy output on a small land footprint, geographic flexibility, and consistent zero-carbon energy supply that may justify these higher capital costs. Some aspects of nuclear energy do, however, improve its cost-competitiveness as compared to renewable and fossil generation. Nuclear fuel costs are typically lower than other sources, such as coal or natural gas.[49] Nuclear plants are also long-lived assets that could produce zero-carbon energy into the next century, enabling capital costs to be spread over a longer period of active energy generation.[50] In addition, costs are likely to decline as a result of learning-by-doing as more advanced reactors are deployed. As a result, Nth-of-a-kind (NOAK) deployments (the later generations of the technology) may be more cost-competitive than the first-of-a-kind (FOAK) projects, as illustrated in Figure 5.[51]

FIGURE 5: Project NOAK Overnight Capital Cost by Learning Rate



The potential effect of learning-by-doing (characterized as the learning rate, or rate at which the cost of a technology decreases as the deployed capacity increases) on the overnight capital costs of nascent nuclear reactors as more reactors are deployed.

Source: U.S. Department of Energy, Pathways to Commercial Liftoff: Advanced Nuclear (Washington, DC: U.S. DOE, 2023), https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf.

Follow-on effects from initial investments and deployments will likely increase confidence in advanced nuclear energy implementation. For example, the collaboration between X-energy and Dow has led other companies to consider nuclear technology as a clean energy option to decarbonize their industrial sites' energy and heat needs. Energy Northwest, a clean electricity provider, recently announced their joint development agreement with X-energy for a 12-unit Xe-100 SMR power plant in Washington capable of generating a total of 960 MW of electricity, or 2.4 GW of high-temperature steam.[52] In a statement, Energy Northwest noted, "as X-energy demonstrates its technology alongside Dow as part of ARDP, we will support and learn from their work to optimize, deliver, and develop future projects together. Working collaboratively to deploy multiple advanced reactors in a short timeframe will be beneficial to both Dow and Energy Northwest, as well as to the entire advanced nuclear industry."[53] This increased confidence in advanced nuclear technologies and more cost-efficient deployment (as illustrated in Figure 5) will likely reduce the overnight capital costs of advanced reactor projects.

REGULATORY RISK AND DELAY

The long regulatory process is another challenge to rapidly deploying advanced nuclear technologies. Before, during, and after construction, the NRC is required to review and approve the construction and operation of all nuclear energy facilities. The application process includes environmental reviews, safety reviews, and administrative hearings.[54] With a range of new reactor types coming up for review, long lead times in the licensing process may be a serious hurdle for novel nuclear projects, which can take up to five years to complete.[55]

Additionally, advanced reactors under development differ from existing reactors in ways that affect the review process. For example, they are much smaller, use different mechanisms, and have passive safety features that do not require extensive staffing and design redundancies.[56] Rules will need to be updated for advanced reactors. Current rules were developed for conventional technologies, so without updates they would likely require regulatory exemptions and alternative requirements to apply to newer technology. Without updates, the current review process could limit innovation and become burdensome to new designs.[57]

NuScale's SMR was the first SMR to be approved by the NRC, receiving design certification in 2023 after 41 months of review. This approval was separate from the combined license (COL), which authorizes construction and operation of a nuclear plant at a specific site for a time period of 40 years.[58] This long review would likely be even longer for other SMR reactors that use novel technologies. The NuScale design is a light-water reactor similar to the current fleet of certified reactors; newer designs may be more challenging and time-intensive to license initially.[59]

Applicants can work with the NRC to reduce the timeline of the licensing process by engaging with the agency before submitting their application (typically called pre-application interactions), thereby minimizing back-and-forth communication during the formal review process that slows the review. Open communication between developers and the NRC before the submission of applications can expedite the review process, as developers will have a better understanding of expectations, and the NRC will have fewer questions about design later in the process.

The need to expedite advanced nuclear reactor licensing has been recognized internationally, and solutions are currently under development. In March 2024, the United States, Canada, and the United Kingdom signed a Memorandum of Cooperation to collaborate on shared technical review approaches and improve regulatory effectiveness in each country.[60] The NRC has already started working with the Canadian Nuclear Safety Commission to test a risk-informed regulatory cooperation process, aiming to create a more standardized licensing process for projects such as Westinghouse's eVinci microreactor and X-energy's Xe-100.[61] In addition, as described later, the NRC has been pursuing a range of reforms to accelerate the process of licensing advanced nuclear technologies.

NUCLEAR FUEL SUPPLY CHAIN

As interest in expanding U.S. nuclear energy capabilities has risen, the security of the nuclear fuel supply chain has become a source of concern. Currently, nearly all uranium used in U.S. commercial reactors is imported; domestic production accounts for only about five percent of U.S. reactor fuel.[62] The United States imports uranium from multiple countries, with the most coming from Canada, Kazakhstan, Russia, Uzbekistan, and Australia.[63] Additionally, there is no significant domestic production of the high-assay low-enriched uranium (HALEU) needed for most advanced nuclear designs, posing energy security risks along with supply chain instability as the United States looks toward increasing deployment of advanced designs.[64]

The prominence of Russia in the nuclear supply chain is particularly problematic. Russia provides about 24 percent of the United States' enriched uranium, and prior to the recent Centrus demonstration project in Piketon, Ohio, was the source of all commercially produced HALEU. In 2023, Centrus produced the first domestically manufactured HALEU in decades and will continue ramping up production, building domestic capacity.[65] Recent U.S. policy has banned the import of low-enriched uranium from Russia beginning in August of 2024; the extent and outcome of this policy is unclear at this time. If entities are not able to obtain supplies elsewhere, they can apply for a waiver that allows the import of low-enriched uranium fuel, through 2028.[66] Congress passed the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act in June of 2024, which expanded the definition of 'covered fuel' to include fuel that is fabricated in Chinese-owned entities, as well as in Russian-owned entities. It prohibits U.S. commercial nuclear from possessing enriched uranium fuel fabricated by these entities unless specifically authorized by the NRC and Energy and State secretaries[67] If the United States is to avoid future fuel supply disruptions (which could rapidly increase fuel prices and compromise energy production) a strong commitment to domestic fuel production is essential to help increase energy security.[68]

WORKFORCE

There is a need for increased training and education programs to create a robust nuclear workforce of skilled nuclear engineers, electricians, construction workers, nuclear manufacturers, operators, and other workers. A highly trained workforce is critical to meet the demand for advanced nuclear technology development and deployment. However, the United States has built very few nuclear plants in recent decades, and the nuclear workforce generally reflects that reality.[69] If the current lack of workforce expertise is not remedied through training programs, the anticipated surge in nuclear construction projects will take longer and cost more. Notably, the recently trained workforce from the Vogtle AP1000 projects in Waynesboro, Georgia, should decrease the amount of training needed for future projects, but only if the projects are built within the next decade or so.[70]

The growth of the advanced nuclear power industry will spur long-term job creation across the United States. The U.S. nuclear power industry directly employes nearly 60,000 workers in well-paying, career-length jobs, and indirectly employs over 400,000 other workers.[71] As nuclear facilities are built, many jobs are created during the construction phase, and there are also long-term jobs to operate, supply, and manage completed facilities.[72] If international demand for U.S.-designed nuclear power plants eventuates, economic activity and domestic workforce demands to support exports would increase commensurately.

Communities with existing fossil fuel-powered plants also have an opportunity to retain and reskill local workers for sustainable, well-paying jobs with adequate support and planning for training.[73] A coal-to-nuclear power plant transition could create hundreds of additional, higher-paying jobs locally, and spur millions of dollars in economic activity in communities, along with increased revenue along the nuclear supply chain, including power plant operators and local suppliers. SMRs are particularly well-suited to replace aging coal plants for various previously discussed attributes, including their relatively small physical footprint, geographic independence, enhanced safety features, and lower capital costs.[74]

SPENT FUEL MANAGEMENT

Developing a permanent repository for spent nuclear fuel has been a challenge for the nuclear industry since its inception. Proper management of highly radioactive spent nuclear fuel is essential to making nuclear energy a viable option in the clean energy transition. Currently, spent fuel rods are stored onsite at nuclear plants, initially in specially designed spent fuel pools that cool the waste for several years, and later in dry storage containers. The NRC is confident that current spent fuel storage is safe for "at least 60 years beyond the life of any reactor without significant environmental effects."[75] While there is sufficient space at existing facilities to continue to store spent fuel for decades, the accumulation of spent fuel has raised concerns about the lack of a long-term storage plan; finding a policy solution for this issue would help existing and future reactors.[76]

Some advanced nuclear power developers are exploring using spent fuel from previous nuclear reactors in their own reactor designs; this would reduce the existing stockpile of 'waste' fuel and the amount of new reactor fuel needed for energy production. Oklo's Aurora nuclear microreactor, for example, is capable of using recycled spent fuel, creating the opportunity for lower operating costs while decreasing the amount of spent fuel produced during clean energy generation. Oklo has received over $15 million from the DOE to develop its waste-to-energy fuel recycling technology.[77]

STATE BANS & PUBLIC SUPPORT

Several states have policies that discourage or outright prohibit new nuclear energy facilities. Twelve states currently have restrictions—such as requiring voter or state legislature approval (or both) or requiring an acceptable means of spent fuel disposal or reprocessing to be in place—or full bans on any new nuclear construction. Such state restrictions hinder the ability of advanced nuclear reactors to serve as a decarbonization solution. However, in recent years, six states have rolled back their restrictions, and some have repealed their bans altogether.[78]

Even though public approval of nuclear power in the United States is at an all-time high, continued education on advanced nuclear is still needed to increase and solidify support and promote informed discussions at the local, state, and national levels.[79] Misconceptions about nuclear power are still pervasive, and local and state opposition can still present obstacles. Private developers and industrial facilities need to engage the communities they are considering for nuclear deployment early and often. For example, when Dow was exploring which site it might select to deploy nuclear technology, early engagement with communities with ample time to ask questions and fully understand the project was key to developing community trust and support. The company hosted briefings alongside X-energy with local elected leaders to answer questions about the technology, safety, and workforce. They had additional events with neighbors to educate local stakeholders on the project and continued to maintain open lines of communication throughout the decision process. Overwhelmingly, local stakeholders were receptive and supportive of the project.[80]

RECENT POLICY ACTIONS TO ADDRESS CHALLENGES

The U.S. government is increasingly recognizing the value of domestic nuclear energy generation and has taken actions to maintain existing nuclear and achieve successful deployments of advanced nuclear technologies.

CONGRESS AND DOE

Nuclear energy has received strong support through recent federal legislation, including the Inflation Reduction Act (IRA) of 2022, the Infrastructure Investment and Jobs Act (IIJA) of 2021, and the Energy Act of 2020.

The IRA provides tax incentives and funds a fuel program to support nuclear energy production through various avenues. Table 2 highlights some of the key IRA supports for nuclear deployments.

In addition to the hundreds of millions of dollars the IRA provides to support domestic HALEU production, Congress recently passed legislation expanding programs to boost domestic uranium production.[81] Congress also passed a bill banning U.S. imports of Russian uranium, which in turn unlocks more than $2 billion of previously authorized funding to expand U.S. production of nuclear fuel, including HALEU.[82]

The IIJA also provided support for nuclear deployment in a range of ways. For example, the IIJA authorized an additional $2.5 billion in cost-shared funding for DOE's ARDP, which will help support the design, licensing, construction, and operation of two advanced nuclear technologies (TerraPower and X-energy) in the near- and mid-term.[83] (In cost-shared partnerships, the government awards a certain percentage of the total project funding, and the private U.S. industry partner contributes the remaining portion of the project cost.) The award also signals technical acceptance to the market. The IIJA also invested $6 billion in a Civil Nuclear Credit Program at DOE to extend the operation of existing U.S. nuclear plants.[84]

DOE's Loan Program Office (LPO) finances advanced nuclear energy projects through several avenues. The LPO makes early investments in next-generation U.S. energy infrastructure so they may develop to commercial scale. One avenue is the Title 17 Clean Energy Finance Program, which was created by the Energy Policy Act of 2005 and most recently amended by the IRA and IIJA.[85] This support includes about $62 billion in loan guaranty authority for innovative technologies through the Title 17 Innovative Clean Energy Loan Guarantee Program, including domestic manufacturing of components in the nuclear supply chain. Additionally, the Title 17 Energy Infrastructure Reinvestment Program received $250 billion from the IRA to retool, repower, repurpose, or replace retired energy infrastructure or to enable the avoidance or sequestration of greenhouse gas emissions, which could include the conversion of coal plants to nuclear power plants.[86]

DOE also has RD&D programs that aim to tackle some of the challenges facing advanced nuclear deployment. For instance, the Advanced Research Projects Agency – Energy (ARPA-E) created the ONWARDS program to develop technologies that reduce advanced reactor waste through recycling and the development of high-performance waste forms.[87] ARPA-E also created the Converting UNF Radioisotopes Into Energy (CURIE) program, which is working on minimizing used nuclear fuel (UNF) by reprocessing it into new fuel for advanced reactors.[88]

Opportunities for nuclear to support the decarbonization of industrial heat can also be furthered by programs and policies not directly focused on nuclear (and clean electricity). For example, the DOE Industrial Demonstrations Program has $6.3 billion (also from the IIJA and the IRA) to support advancements in technologies that reduce emissions in industrial sectors such as steel, cement, paper, and ceramics.[89]

There has also been significant federal activity around hydrogen that could make nuclear hydrogen production more cost-competitive. For instance, the IRA's hydrogen PTC (Section 45V) could allow nuclear reactors to qualify for up to ten years of tax credits for output from a clean hydrogen production facility, though whether both new and existing reactors could qualify will depend on final determinations made by the Internal Revenue Service.[90] In addition, the IIJA directed substantial funding into a DOE Regional Clean Hydrogen Hubs program to rapidly advance a network of clean hydrogen producers, increase end use, and develop transportation and storage infrastructure. Two of the seven hubs selected to receive

TABLE 2: Inflation Reduction Act Support for Nuclear Energy Production

IRA Program Title	Program Description	Period of Availability
Section 45Y Clean Electricity Production Tax Credit (PTC)[22]	This replaces the existing Section 45 PTC in 2025 and aims to provide a technology-neutral incentive for clean electricity production and zero-carbon combined heat and power. The base amount—0.3 cents per kilowatt-hour (kWh)—may be increased by variable amounts if the facility meets eligible wage and apprenticeship standards, is located in an energy community, or meets domestic content requirements.	Available for facilities placed in service after 2024; phaseout begins when U.S. greenhouse gas emissions are 25% of 2022 levels, or 2032, whichever is later. This credit is for new and incremental generation.
Section 48E Clean Electricity Investment Tax Credit (ITC)[23]	This replaces the existing Section 48 ITC in 2025 and incentivizes technology-neutral investments into new zero-carbon power plants and energy storage technologies. The base amount (6% of qualified investment) may be increased by variable amounts if the facility meets eligible wage and apprenticeship standards, is located in an energy community, or meets domestic content requirements.	Available for facilities placed in service after 2024; phaseout begins when U.S. greenhouse gas emissions are 25% of 2022 levels, or 2032, whichever is later. This credit is for new and incremental generation.
Section 45U Zero-Emission Nuclear Power PTC[24]	This production tax credit grants 0.3¢ for every kWh of electricity produced at a qualified nuclear power facility and sold to another person. The base amount can be increased if wage and apprenticeship requirements are met. This cannot be used with 45J, below.	Available for electricity produced and sold starting in 2024, available through the end of 2032. This credit is primarily aimed at existing nuclear power.
Section 45J Advanced Nuclear PTC[25]	This PTC, updated by IRA, grants 1.8¢ for every kWh of electricity produced and sold by a taxpayer at an advanced nuclear power facility (with limitations).	Available for the production of energy during the facility's first 8 years.[26] This credit is for new and incremental generation.
HALEU Availability Program[27]	The IRA approved $700 million to help accelerate the establishment of a domestically produced HALEU supply chain for commercial use in advanced reactors. Additional funds were authorized for other research, development, and deployment (RD&D) programs to support other nuclear technologies at DOE national labs, including the production of domestic HALEU fuel.	This funding will be available through September 2026.

Credits such as Section 45Y and 48E, though directly encouraging clean electricity, indirectly incentivize clean industrial heat production by creating economic conditions that are conducive to clean energy projects such as nuclear power, which are capable of creating clean heat as a byproduct of electricity generation.

part of the $7 billion in total funding—the Mid-Atlantic Hydrogen Hub and the Midwest Hydrogen Hub—specifically plan to produce hydrogen from nuclear energy.[91] DOE's Clean Hydrogen Electrolysis Program, also funded through appropriations from the IIJA, will continue to reduce risk and cost associated with commercializing and deploying clean hydrogen production through the development and commercialization of electrolyzers, which would improve the economics of nuclear hydrogen production.[92]

Similarly, support for CCUS technology, especially the $12 billion investment from the IIJA and the IRA's expansion of the CCUS tax credit (Section 45Q), will ease the financial risk of deploying CCUS powered by nuclear energy when manufacturing processes cannot be fully decarbonized by switching to clean fuel, such as in the cement sector.[93]

NUCLEAR REGULATORY COMMISSION

Congress has also pushed the NRC to better prepare for the deployment of advanced nuclear technologies, such as in the Nuclear Energy Innovation and Modernization Act of 2019.[94] In response, the NRC has taken a range of steps to reduce regulatory risk for advanced reactors.[95]

The NRC is currently developing a new regulation (10 CFR Part 53) to create an optional, risk-informed, performance-based, and technology-inclusive framework for licensing future advanced nuclear reactors while ensuring adequate mitigation of risk. It aims to strike a balance between assuring the safety of nuclear facilities while developing them at a reasonable speed and affordable cost. Some developers have expressed concern about the complexity and cost of the proposed Part 53 rule, and others with experience navigating the traditional regulations from previous designs prefer to retain that process knowledge. Still others plan to start the approval process before Part 53 is finalized in 2026 or 2027.[96] Continued discussion and analysis will help to further refine the licensing process.

The NRC has made efforts to provide flexible licensing avenues to developers while they await final adoption of the Part 53 rule. The NRC has taken recent action to streamline the application process through office reorganization and publications intended to aid reactor developers and better prepare them for the licensing process.[97] For example, to achieve NRC licensing of its Xe-100 reactor, X-energy will be following the NRC-approved methodology described in the Nuclear Energy Institute (NEI) 18-04 regulatory guide, the "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development," released in 2019.[98] The guide, which is a result of the Licensing Modernization Project (LMP) led by NEI and Southern Company and cost-shared with DOE, defines an acceptable approach for informing the licensing basis and determining the appropriate scope and performance criteria to properly evaluate the safety of advanced reactor designs.[99] The approach allows applicants to license designs under the existing regulatory framework, using regulatory exemptions to meet criteria optimized for large, traditional reactors. X-energy will be one of the first companies to use NEI 18-04 to license its reactor. X-energy has been engaging with the NRC in anticipation of their submission to try to identify areas of potential NRC concern or questions. Once the process is tested through the Xe-100 application and becomes more familiar to NRC staff, other advanced reactors should be able to use the risk-informed LMP framework to license their own designs more easily.

BOX 4: Summary of Recommendations

Additional financial and technical support: Congress and government agencies such as DOE should expand financial and technical support for the deployment of advanced nuclear reactor technologies (inclusive of fuel and other supplies), for workforce development, and for industrial facilities looking to adopt advanced nuclear technologies.

NRC action and support: Congress and the NRC should continue efforts to finalize new, more efficient licensing procedures for advanced nuclear reactors, and congress should deliver additional NRC staff and resources to better handle the anticipated volume of applications for new reactors in the near future.

Carbon pricing: Congress should implement a federal price on greenhouse gas emissions to incentivize emissions reductions through a market-based incentive, which would improve the cost-competitiveness of industrial decarbonization efforts and encourage the deployment of innovative advanced nuclear technologies and fuels.

POLICY RECOMMENDATIONS

Although momentum behind the development and deployment of advanced nuclear technologies is building, there are several policies Congress could adopt to further mitigate the challenges to expanding U.S. nuclear energy generation in industrial applications.

ADDITIONAL FINANCIAL & TECHNICAL SUPPORT

Government support for RD&D is essential to develop innovations that private investments will not or cannot take on alone. While the IRA and IIJA, along with other pieces of legislation, have authorized historic funding for nuclear energy development through grants, government cost-sharing, and tax credits, additional support for advanced nuclear demonstration projects will further ease financial hurdles and foster a self-sustaining market. Additional support for fuel fabrication and authorization will be essential to support the growth of nuclear energy, especially considering recent congressional action banning some imports of nuclear fuel. In addition, policy support for a handful of early SMR projects, such as government-provided cost overrun insurance (to cover project construction costs above a certain threshold), would reduce risks associated with first-of-a-kind projects that might otherwise deter project owners.[100] (Such insurance could theoretically be provided by a private-sector entity as well.) Government funding and oversight of nuclear workforce development training programs are also needed, including in higher education facilities, trade and technical schools, and high schools.

Tax credits that support nuclear and related technologies start phasing out in the early 2030s (or when emissions are 25 percent of 2022 levels). These need to be extended to provide a clear signal that will support the economic viability of emerging clean energy projects with longer timelines, which would increase the feasibility of all developing zero-carbon technologies including nuclear technologies.[101] Nuclear energy projects take many years to plan, execute, and enter operations (and many advanced designs are at low technology readiness levels). If a facility is currently being planned, it will be many years before it can start producing clean energy eligible for production tax credits, at which time the current tax credits may have already expired. We support the recommendation in the U.S. Department of Treasury and Internal Revenue Service proposed guidance on the technology neutral tax credits (45Y and 48E). The guidance qualifies nuclear fission and fusion electricity generation facilities, including those that are "dedicated to heat production for an industrial facility", as types of facilities that would qualify for these credits under the category of Non-Combustion and Gasification facilities with a greenhouse gas emissions rate not greater than zero. As proposed, all nuclear electricity and the useful heat generated (i.e., BTUs converted to kWh) by a facility would receive credit, creating a strong incentive for nuclear CHP.[102]

It would also be helpful to expand existing federal technical support to include nuclear applications, to better assist communities and innovators in navigating the challenges of establishing new nuclear facilities. For example, programs such as DOE's Onsite Energy Technical Assistance Partnerships provide direct technical assistance to industrial facilities on projects to meet site-specific energy goals, from the early planning stages through the operation of projects. Currently, supported technologies include battery storage, solar, geothermal, thermal storage, fuel cells, industrial heat pumps, and renewable fuels; CHP applications are eligible for technical assistance as well, but it is not clear whether that includes nuclear applications.[103] Adding specific technical support fact sheets and decision-making tools for nuclear facility planning and implementation processes could encourage adoption of more advanced nuclear thermal solutions.

NRC ACTION AND SUPPORT

The NRC has helped to ensure the safety of nuclear power for more than half a century, and as noted earlier, it is taking steps to modify its review and licensing processes to better evaluate new designs, shifting to a more risk-informed, performance-based approach. The NRC must continue its efforts to finalize its new Part 53 rule.

Increased support for the NRC will be essential in preparing for and reacting to the anticipated increased workload at the NRC as more advanced nuclear reactor designs submit construction applications for review. In June 2024, Congress passed the ADVANCE Act, which would, among other things, better equip the NRC with tools and staff to meet the anticipated volume of new reactor designs and deployments in the coming decades. It also requires the NRC to update its mission statement so it does not "unnecessarily limit" the use of nuclear energy, requires more timely processing of license applications, and includes provisions to augment the NRC's workforce.[104] Congress passed the ADVANCE Act in an effort to improve NRC licensing procedures and workforce acquisition, mitigating anticipated bureaucratic bottlenecks; its success will depend on the NRC effectively implementing these enhancements in a timely and judicious manner.

CARBON PRICING

Carbon pricing, which could include carbon taxes or cap-and-trade programs, is a market-driven solution that allows polluters to choose their own emission reduction strategy in response to market rules. Several jurisdictions have implemented cap-and-trade programs, which have succeeded in reducing emissions. A federal carbon price could provide a strong nationwide economic signal for industry and other sectors to reduce emissions by switching to cleaner alternatives.[105] In particular, a carbon price would make advanced nuclear solutions more cost-competitive, and therefore more attractive options to meet the thermal needs of high-temperature industries.

CONCLUSION

The U.S. industrial sector is a significant contributor to U.S. emissions, and it faces somewhat unique decarbonization challenges due to its electricity and heating needs (in addition to process emissions in some industries). Developing and deploying advanced nuclear energy facilities could provide a promising, flexible pathway to enable decarbonization of industrial heat. Advanced nuclear can provide high temperature outputs directly and/or power other decarbonization technologies such as electrolytic hydrogen production and CCUS, and it can do so in a way that is geographically flexible, enhances grid resilience, provides modularity, and has a small land footprint.

Nuclear power and other clean heat solutions must be further developed and deployed through strong policy levers and continued demonstration in order to meaningfully and rapidly decarbonize the industrial sector.

C2ES Resources

Solutions for Maintaining the Existing Nuclear Fleet
https://www.c2es.org/document/solutions-for-maintaining-the-existing-nuclear-fleet/

Clean Industrial Heat: A Technology Inclusive Framework
https://www.c2es.org/document/clean-industrial-heat-a-technology-inclusive-framework/

Clean Heat Pathways for Industrial Decarbonization
https://www.c2es.org/document/clean-heat-pathways-for-industrial-decarbonization/

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

Reaching for 2030: Climate and Energy Policy Priorities
https://www.c2es.org/document/reaching-for-2030-climate-and-energy-policy-priorities/

Decarbonizing U.S. Industry
https://www.c2es.org/document/decarbonizing-u-s-industry/

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As a fully independent organization, C2ES is solely responsible for the findings of this work, and acknowledgment of contribution does not necessarily indicate endorsement of the report's findings.

ENDNOTES

1 Elliot Diringer et al., Getting to Zero: A U.S. Climate Agenda (Arlington, VA: Center for Climate and Energy Solutions, 2019), *https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/*.

2 This paper will focus on the potential for nuclear reactors to decarbonize industrial process heat; as such, the use of nuclear power for electricity generation, though important, is largely out of this paper's scope; Advanced nuclear reactors are those that use different technologies from existing operating reactors such as different fuel or coolant, greater use of passive safety features, or smaller scale reactors, and are often more efficient, safer, and more cost-effective than conventional reactors. Small modular reactors, those that generate less than 300 MW, are among these advanced reactor designs. This paper examines the unique opportunity for advanced reactors, especially small modular reactors, to decarbonize industrial heat demand. Vincent Gonzales and Lauren Dunlap, "Advanced Nuclear Reactors 101," Resources for the Future, March 26, 2021, *https://www.rff.org/publications/explainers/advanced-nuclear-reactors-101/*.

3 International agreements help to prevent the diversion of civilian nuclear material and limit the proliferation of nuclear weapons. The International Atomic Energy Association regularly inspects and monitors civilian nuclear power facilities around the world. World Nuclear Association, "Safeguards to Prevent Nuclear Proliferation, May 6, 2021, *https://world-nuclear.org/information-library/safety-and-security/non-proliferation/safeguards-to-prevent-nuclear-proliferation*; So-called "123 Agreements" must exist between the United States and foreign countries before civilian nuclear facilities can be constructed by U.S. nuclear companies. These agreements provide an additional layer of security in helping to advance non-proliferation principles. U.S. Department of Energy, "123 Agreements for Peaceful Cooperation," February 20, 2024, *https://www.energy.gov/nnsa/123-agreements-peaceful-cooperation*.

4 U.S. Department of Energy, Industrial Decarbonization Roadmap (Washington, DC: U.S. DOE, 2022), *https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf*.

5 "U.S. Energy Facts Explained," U.S. Energy Information Administration, last modified August 16, 2022, *https://www.eia.gov/energyexplained/us-energy-facts/*.

6 This number accounts for direct and indirect greenhouse gas emissions. "Controlling Industrial Greenhouse Gas Emissions," Center for Climate and Energy Solutions, accessed January 30, 2024, *https://www.c2es.org/content/regulating-industrial-sector-carbon-emissions/*.

7 Renewable Thermal Collaborative, Industrial Thermal Decarbonization Package (Arlington, VA: RTC, 2022), *https://www.renewablethermal.org/wp-content/uploads/2018/06/Decarbonization_FullPackage_Updated-Sept-2023.pdf*.

8 Renewable Thermal Collaborative, The Renewable Thermal Vision: Finding a Path Forward for Decarbonizing Thermal Energy in the U.S. Industrial Sector (Arlington, VA: RTC, 2022), *https://www.renewablethermal.org/vision/*.

9 Ibid.

10 Solar thermal systems are geographically constrained as they are dependent on the amount of sunlight they are able to collect. "Solar explained, Solar thermal power plants," U.S. Energy Information Administration, last modified April 15, 2022, *https://www.eia.gov/energyexplained/solar/solar-thermal-power-plants.php*; Renewable Thermal Collaborative, The Renewable Thermal Vision: Finding a Path Forward for Decarbonizing Thermal Energy in the U.S. Industrial Sector (Arlington, VA: RTC, 2022), *https://www.renewablethermal.org/vision/*.

11 Electrification technologies such as electric arc furnaces require large amounts of electricity to reach high temperatures. The current U.S. electrical grid will require significant build-out of power sector infrastructure and increased clean electricity generation and storage to successfully decarbonize industrial high-temperature process heat using these technologies. Doug Vine and Chris Henderson, Clean Heat Pathways for Industrial Decarbonization (Arlington, VA: Center for Climate and Energy Solutions, 2021), *https://www.c2es.org/wp-content/uploads/2021/08/C2ES_Industrial-Clean-Heat_FINAL6.pdf*.

[12] Katherine Antonio, “Renewable generation surpassed coal and nuclear in the U.S. electric power sector in 2022,” U.S. Energy Information Administration, March 27, 2023, *https://www.eia.gov/todayinenergy/detail.php?id=55960*; “Nuclear Power in the World Today,” World Nuclear Association, last modified November, 2023, *https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx*.

[13] “Nuclear Power in the World Today,” World Nuclear Association, last modified November, 2023, *https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx*; “Nuclear Power in the USA,” World Nuclear Association, last modified January 2024, *https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx*.

[14] “U.S. Nuclear Plants,” Nuclear Energy Institute, last modified April, 2023, *https://www.nei.org/resources/fact-sheets/u-s-nuclear-plants*.

[15] Nuclear power plants operate independently of geographical constraints, making them viable for sites lacking good access to natural resources such as sun, wind, or geothermal reservoirs that other clean energy sources would require; Nuclear Energy Institute, “Land Needs for Wind, Solar Dwarf Nuclear Plant’s Footprint,” July 9, 2015, *https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants*.

[16] “Are there different types of nuclear reactor?,” World Nuclear Association, accessed January 31, 2024, *https://www.world-nuclear.org/nuclear-essentials/are-there-different-types-of-reactor.aspx*; Emma Derr, “Nuclear Needs Small Amounts of Land to Deliver Big Amounts of Electricity,” Nuclear Energy Institute, April 29, 2022, *https://www.nei.org/news/2022/nuclear-brings-more-electricity-with-less-land*.

[17] SMRs’ relatively small land footprint and off-grid functionality offer siting flexibility to meet the specific needs of industrial sites. For example, an Xe-100 four module plant capable of generating 300 MW sits on 13 acres of land, whereas the same energy generation capacity would require a 7,200 acre solar array facility or a 120,000 acre wind turbine facility, adjusting for average capacity factors. They are compact enough to power sites that do not have space for other clean technologies and can serve rural areas that would otherwise require substantive infrastructure upgrades to electrify their heat by tapping into the larger electrical grid. X-energy, X-energy Xe-100 Reactor Initial NRC Meeting, (Rockville, MD: X-energy, 2018), *https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML18253A109*; Billy Ludt, “300-MW PV array supports nation’s 1st solar-powered steel mill,” Solar Power World, March 9, 2022, *https://www.solarpowerworldonline.com/2022/03/300-mw-pv-array-supports-nations-1st-solar-powered-steel-mill/*; “Rock Creek Wind Farm, Atchison County, Missouri,” NS Energy, accessed April 4, 2024, *https://www.nsenergybusiness.com/projects/rock-creek-wind-farm-atchison-missouri/*; Acres for Solar generation was multiplied by 4 per a capacity factor of about 25%, and acres for wind generation was multiplied by 3 per a capacity factor of about 33%. “Electric Power Monthly: Table 6.07.B. Capacity Factors for Utility Scale Generators Primarily Using Non-Fossil Fuels,” U.S. Energy Information Agency, accessed April 4, 2024, *https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b*.

[18] A module of an SMR is a small, self-contained unit that can be combined with other units to generate larger amounts of energy. These relatively small modules can be assembled in a factory then easily transported to the operating facility, increasing configuration flexibility.

[19] See Table 1 for more information on new types of fuels. Joanne Liou, “What are Small Modular Reactors (SMRs)?,” International Atomic Energy Agency, September 13, 2023, *https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs*.

[20] U.S. Department of Energy and Allegheny Science & Technology Corporation, Small Modular Reactors: Adding to Resilience at Federal Facilities (Washington, DC: U.S. DOE, 2017), *https://www.energy.gov/sites/default/files/2018/01/f47/Small%20Modular%20Reactors%20-%20Adding%20to%20Resilience%20at%20Federal%20Facilities%20.pdf*; This high level of resiliency makes advanced nuclear promising candidates for locations with low grid reliability. For example, the U.S. territory of Puerto Rico has energy infrastructure that is nearly 30 years older than the average mainland U.S. power plant. In the event of emergencies such as Hurricane Maria in 2017, the entire island has lost power for months at a time, contributing to a higher rate of mortality following the extreme weather. Organizations such as the Nuclear Alternative Project is exploring the potential for SMRs to meet the island’s power needs. Idaho National Laboratory Media Relations, “Bringing Resilient Power to Puerto Rico with Microreactors,” September 3, 2020, *https://inl.gov/nuclear-energy/resilient-power-to-puerto-rico*.

21 International Atomic Energy Agency, Advances in Small Modular Reactor Technology Developments (Washington, D.C.: IAEA, 2022), *https://aris.iaea.org/Publications/SMR_booklet_2022.pdf*.

22 U.S. Department of Energy, “DOE National Laboratory Makes History by Achieving Fusion Ignition,” December 13, 2022, *https://www.energy.gov/articles/doe-national-laboratory-makes-history-achieving-fusion-ignition*.

23 U.S. electricity demand is growing rapidly, in large part due to growth in U.S. population, data centers, artificial intelligence, and innovations such as electric vehicles and electrified industrial heating technologies used in fuel-switching. “Surging electricity demand is putting power systems under strain around the world,” International Energy Agency, January 14, 2022, *https://www.iea.org/news/surging-electricity-demand-is-putting-power-systems-under-strain-around-the-world*.

24 The average operating heat rate listed in the source table is converted to efficiency by dividing the equivalent Btu content of a kWh of electricity (3,412 Btu) by the heat rate. U.S. Energy Information Administration, Average Operating Heat Rate for Selected Energy Sources, 2012 through 2022 (Washington, DC: U.S. EIA, 2022), *https://www.eia.gov/electricity/annual/html/epa_08_01.html*.

25 Paul Day, “Nuclear-powered district heating nears commercialization in Finland,” Reuters Events, July 12, 2023, *https://www.reutersevents.com/nuclear/nuclear-powered-district-heating-nears-commercialization-finland*.

26 Yifan Zhang, Wenan Li, and Qian Yu, “Development Prospect and Application of Nuclear District Heating in China,” Proceedings of the 23rd Pacific Basin Nuclear Conference, Volume 1 (April 2023): 8-17, *https://doi.org/10.1007/978-981-99-1023-6_2*.

27 “Nuclear Power Reactors,” World Nuclear Association, last modified April 2024, *https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx*.

28 Renewable Thermal Collaborative, Industrial Thermal Decarbonization Package.

29 Renewable Thermal Collaborative, Industrial Thermal Decarbonization Package.

30 Dow, “Dow’s Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production,” May 11, 2023, *https://corporate.dow.com/en-us/news/press-releases/dow-s-seadrift--texas-location-selected-for-x-energy-advanced-sm.html*.

31 “Xe-100: The Most Advanced Small Modular Reactor,” X-energy.

32 Doug Vine, Clean Industrial Heat: A Technology Inclusive Framework (Center for Climate and Energy Solutions, 2021), *https://www.c2es.org/wp-content/uploads/2021/10/Clean_Industrial_Heat_A_Technology_Inclusive_Framework.pdf*.

33 Dow, “Dow’s Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production,” May 11, 2023, *https://corporate.dow.com/en-us/news/press-releases/dow-s-seadrift--texas-location-selected-for-x-energy-advanced-sm.html*.

34 “CHP Benefits,” U.S. Environmental Protection Agency, last modified November 13, 2023, *https://www.epa.gov/chp/chp-benefits*.

35 CHP was responsible for 4% of U.S. natural gas consumption in 2022, or 1.36 Tcf. U.S. Energy Information Administration, How much natural gas is consumed in the United States? (Washington, DC: U.S. EIA, 2022), *https://www.eia.gov/tools/faqs/faq.php?id=50&t=8*.

The average carbon dioxide coefficient of natural gas is 0.0550 kg CO2 per cubic foot. U.S. Environmental Protection Agency, Greenhouse Gases Equivalencies Calculator - Calculations and References (Washington, DC: U.S. EPA, 2024), *https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references*.

Conversion of 2022 CHP consumption of natural gas to metric tons of CO_2:

- 1.36 Tcf x 0.0550 kg CO_2/cubic ft = 74800000000 kg CO_2
- 74.8 billion kg CO_2 in 2022
- 1 kg = 0.001 metric tons
- 74.8 million metric tons CO_2 in 2022

36 Ibrahim Dincer and Marc A. Rosen, “Chapter 6 - Heat Storage Systems,” in Exergy Analysis of Heating, Refrigerating and Air Conditioning, ed. Ibrahim Dincer, Marc A. Rosen (Amsterdam: Elsevier, 2015), 221-278.

37 “Natrium Reactor and Integrated Energy Storage,” TerraPower, accessed January 31, 2024, *https://www.terrapower.com/our-work/natriumpower/*.

38 “Hydrogen Storage,” Hydrogen and Fuel Cell Technologies Office, accessed January 31, 2024, *https://www.energy.gov/eere/fuelcells/hydrogen-storage*.

39 “Hydrogen Explained,” U.S. Energy Information Administration, last modified June 23, 2023, *https://www.eia.gov/energyexplained/hydrogen/*.

40 International Atomic Energy Agency, Advances in Nuclear Power Process Heat Applications (Vienna, Austria: IAEA, 2012), *https://www-pusb.iaea.org/MTCD/Publications/PDF/TE_1682_web.pdf*.

41 Thomas Koch Blank et al., “Clean Energy 101: The Colors of Hydrogen,” Rocky Mountain Institute, April 13, 2022, *https://rmi.org/clean-energy-101-hydrogen/*.

42 “Hydrogen Production and Uses,” World Nuclear Association, last modified November 2021, *https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx*.

43 Already, Constellation Energy, the nation’s largest clean energy generator, has invested in building out their commercial hydrogen cogeneration capabilities from their existing nuclear plants. They received nearly $5.8 million from the DOE in cost-shared funding to demonstrate low-cost, scalable low-carbon hydrogen generation at the Nine Mile Point nuclear plant in New York. Their hydrogen is currently used for plant operations, replacing hydrogen produced by fossil fuels that had previously been transported to the site on trucks. Constellation, “Constellation Starts Production at Nation’s First One Megawatt Demonstration Scale Nuclear-Powered Clean Hydrogen Facility,” March 7, 2023, *https://www.constellationenergy.com/newsroom/2023/Constellation-Starts-Production-at-Nations-First-One-Megawatt-Demonstration-Scale-Nuclear-Powered-Clean-Hydrogen-Facility.html*; Office of Nuclear Energy, “Nine Mile Point Begins Clean Hydrogen Production,” March 7, 2023, *https://www.energy.gov/ne/articles/nine-mile-point-begins-clean-hydrogen-production*.

44 Office of Nuclear Energy, “Could Advanced Reactors Make Carbon Capture Systems More Viable?” September 7, 2023, *https://www.energy.gov/ne/articles/could-advanced-reactors-make-carbon-capture-systems-more-viable*.

45 Office of Fossil Energy and Carbon Management, “Selections for Funding Opportunity Announcement 2560: Direct Air Capture Combined with Dedicated Long-Term Carbon Storage, Coupled to Existing Low-Carbon Energy,” April 14, 2022, *https://www.energy.gov/fecm/articles/selections-funding-opportunity-announcement-2560-direct-air-capture-combined*.

46 Cost overruns typically result from either poor project management or first-of-a-kind costs. In the 1960s and 1970s, the U.S. used to build a lot of reactors without cost overruns, then started having lots of cost overruns. However, other countries have built plants fairly recently without cost overruns. First-of-a-kind cost overruns were a problem for Vogtle and may be a problem for early advanced reactors. R. Gene Clark et al., An Analysis of Nuclear Power Plant Construction Costs (Washington, D.C.: Energy Information Administration, 1986), *https://www.osti.gov/servlets/purl/6071600*.

47 For example, a cost overrun of 150% would be an order of magnitude smaller when constructing a $2 billion SMR project (additional $1 billion), rather than a $20 billion traditional project (additional $10 billion).

48 “Economics of Nuclear Power,” World Nuclear Association, last modified August, 2022, *https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx*; This source details the cost difference between carbon-free technologies such as nuclear and solar thermal, compared to their heat rates. U.S. Energy Information Administration, Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2023 (Washington, D.C.: EIA, March 2023), *https://www.eia.gov/outlooks/aeo/assumptions/pdf/elec_cost_perf.pdf*.

49 “Lower wholesale power prices reduce quark spreads available to nuclear plant operators,” Energy Information Administration, April 24, 2013, *https://www.eia.gov/todayinenergy/detail.php?id=10971*.

50 It is worth noting that repayment schedules for capital financing (i.e., bonds) do not correspond to the asset's full lifetime, as valuation focuses significantly on the short- and medium-term. An SMR with an 80-year useful life must pay back its financing within 15-30 years, depending on the terms of the financial instrument. However, the community and grid will benefit from the full 80–100-year lifespan of the project.

"What's the Lifespan for a Nuclear Reactor? Much Longer Than You Might Think," Office of Nuclear Energy, April 16, 2020, *https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think*.

51 U.S. Department of Energy, Pathways to Commercial Liftoff: Advanced Nuclear (Washington, DC: U.S. DOE, 2023), *https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf*.

52 X-energy, "Energy Northwest and X-energy Sign Joint Development Agreement for Xe-100 Advanced Small Modular Reactor Project," July 19, 2023, *https://x-energy.com/media/news-releases/energy-northwest-x-energy-joint-development-agreement-xe-100*.

53 Energy Northwest, "Energy Northwest statement on X-energy-Dow announcement," March 1, 2023, *https://www.energy-northwest.com/whoweare/news-and-info/Pages/Energy-Northwest-statement-on-X-energy-Dow-announcement.aspx*

54 "NRC's Environmental Review Process," U.S. Nuclear Regulatory Commission, last modified September 16, 2022, *https://www.nrc.gov/reactors/new-reactors/how-we-regulate/regs-guides-comm/erp.html*.

55 "Nuclear Explained, U.S. Nuclear Industry" U.S. Energy Information Administration, last modified August 24, 2023, *https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php*.

56 "Part 53- Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," U.S. Nuclear Regulatory Commission, last modified November 20, 2023, *https://www.nrc.gov/reactors/new-reactors/advanced/modernizing/rulemaking-and-guidance/part-53.html#overview*.

57 Patrick White, "Next steps on 10 CFR part 53: Updates on developing a new regulatory framework for advanced reactors" (presentation, Washington, D.C., March 29, 2024), *https://www.youtube.com/watch?v=XyNJqZdnUaA*.

58 NuScale, Lessons-Learned from the Design Certification Review of the NuScale Power, LLC Small Modular Reactor (Rockville, MD: NuScale, 2021), *https://www.nrc.gov/docs/ML2105/ML21050A431.pdf*; "§52.104 Duration of combined license," U.S. Nuclear Regulatory Commission, last modified March 24, 2021, *https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0104.html*.

59 Kairos Power's fluoride salt-cooled high temperature reactor (FHR) received construction permit approval from the NRC in late 2023. They plan to build and operate the Hermes low-power demonstration reactor in Oak Ridge, Tennessee as early as 2026. The demonstration reactor will be capable of delivering 35 MW of thermal power, while future commercial reactors will produce 320 MW of thermal power. "Kairos Power Selects East Tennessee Technology Park for Hermes Low-Power Demonstration Reactor," Kairos Power, Accessed April 23, 2024, *https://kairospower.com/tennessee/*.

60 U.S. Nuclear Regulatory Commission, Memorandum of Cooperation (Washington, DC: U.S. NRC, 2024), *https://www.nrc.gov/docs/ML2406/ML24066A026.pdf*.

61 Nuclear Newswire, "U.S., U.K., Canada Collaborate on advanced reactor licensing," March 21, 2024, *https://www.ans.org/news/article-5887/us-uk-canada-collaborate-on-advanced-reactor-licensing/*.

62 "U.S. Nuclear Fuel Cycle," World Nuclear Association, last modified October, 2023, *https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-fuel-cycle.aspx*.

63 "Nuclear Explained, where our uranium comes from," U.S. Energy Information Administration, last modified August 23, 2023, *https://www.eia.gov/energyexplained/nuclear/where-our-uranium-comes-from.php*.

64 Rowen Price, Ryan Norman, and Alan Ahn, "Western Reliance on Russian Fuel: A Dangerous Game," Third Way, September 30, 2023, *https://www.thirdway.org/memo/western-reliance-on-russian-fuel-a-dangerous-game*.

65 Office of Nuclear Energy, “Centrus Produces Nation’s First Amounts of HALEU,” November 7, 2023, *https://www.energy.gov/ne/articles/centrus-produces-nations-first-amounts-haleu*.

66 Prohibiting Russian Uranium Imports Act, H.R.1042, 118th Congress (2024)

67 “Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act, S.1111, 118th Congress, (2024); U.S. Senate Committee on Environment & Public Works, “Senate Passes Bipartisan Nuclear Energy Bill from Capito, Carper, Whitehouse,” July 27, 2023, *https://www.epw.senate.gov/public/index.cfm/2023/7/senate-passes-bipartisan-nuclear-energy-bill-from-capito-carper-whitehouse#*.

68 Price, Norman, & Ahn, “Western Reliance on Russian Fuel: A Dangerous Game.”; Prohibiting Russian Uranium Imports Act, H.R.1042, 118th Congress (2024).

69 “Number of nuclear power reactors in the United States for selected years from 1957 and 2022,” Statistica, last modified January 9, 2024, *https://www.statista.com/statistics/184981/number-of-nuclear-power-plants-in-the-us/*.

70 If future projects in the U.S. take longer to start, these newly skilled workers will require re-training or will be unavailable and an entire new workforce will have to be trained again. Zach Bright, “What Vogtle’s stumbling finish means for U.S. nuclear energy,” E&E News, July 31, 2023, *https://www.eenews.net/articles/what-vogtles-stumbling-finish-means-for-u-s-nuclear-energy/*.

71 River Bennett, Economic Impacts of Nuclear Plants in Communities (Idaho Falls, Idaho: Idaho National Laboratory, 2023) *https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_66912.pdf*.

72 Purdue University and Duke Energy, Small Modular Reactor and Advanced Reactor Feasibility Study Interim Report (West Lafayette, Indiana: Purdue University & Duke Energy, 2023), *https://www.purdue.edu/administrative-operations/nuclear/documents/smr-feasibility-study-interim-report.pdf*.

73 A DOE Study found that hundreds of coal power plant sites across the country could be converted to nuclear power plants sites, dramatically increasing the supply of clean, firm power. J. Hansen et al., Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants, Nuclear Fuel Cycle and Supply Chain (Washington, D.C.: U.S. Department of Energy, 2022) *https://fuelcycleoptions.inl.gov/SiteAssets/SitePages/Home/C2N2022Report.pdf*.

74 More than 300 existing and retired coal plants are suitable to host advanced nuclear plants and technologies. By reusing the existing infrastructure, up to 35% of plant construction costs can be saved, up to 86% of emissions in the surrounding region could be reduced, and communities would see about $275 million of added annual economic activity. U.S. Department of Energy Office of Nuclear Energy, Coal-To-Nuclear Transitions: An Information Guide (Washington, D.C.: U.S. DOE, 2024), *https://www.energy.gov/sites/default/files/2024-05/Coal-to-Nuclear%20Transitions%20An%20Information%20Guide.pdf*.

75 U.S. Nuclear Regulatory Commission, “Spent Fuel Storage in Pools and Dry Casks Key Points and Questions & Answers,” Accessed January 31, 2024, *https://www.nrc.gov/waste/spent-fuel-storage/faqs.html*.

76 Doug Vine, Solutions for Maintaining the Existing Nuclear Fleet (Arlington, VA: Center for Climate and Energy Solutions, 2018), *https://www.c2es.org/wp-content/uploads/2018/05/solutions-for-maintaining-existing-nuclear-fleet.pdf*.

77 “Fuel Recycling,” Oklo, accessed January 31, 2024, *https://oklo.com/fuel-recycling/default.aspx*.

78 “States Restrictions on New Nuclear Power Facility Construction,” National Conference of State Legislatures, last modified September 28, 2023, *https://www.ncsl.org/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility-construction*.

79 Rebecca Leppert and Brian Kennedy, “Growing share of Americans favor more nuclear power,” Pew Research Center, August 18, 2023, *https://www.pewresearch.org/short-reads/2023/08/18/growing-share-of-americans-favor-more-nuclear-power/*

80 X-energy, “Dow’s Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production,” May 11, 2023, *https://x-energy.com/media/news-releases/dows-seadrift-texas-location-selected-for-x-energy-advanced-smr-nuclear-project-to-deliver-safe-reliable-zero-carbon-emissions-power-and-steam-production*.

81 The Energy Act of 2020 required DOE to support the availability of HALEU for demonstration and commercial purposes. It also directed the NRC to identify regulatory requirements for future HALEU use. “Consolidated Appropriations Act, 2021,” H.R. 133, 116th Congress, Sec. 2001, 2020)

82 Prohibiting Russian Uranium Imports Act, H.R.1042, 118th Congress (2024); National Defense Authorization Act for Fiscal Year 2024, 118th Congress, Sec. 3131 (2023).

83 The Energy Act of 2020 reauthorized the ARDP after the program was launched by DOE in May 2020. “Consolidated Appropriations Act, 2021,” H.R. 133, 116th Congress, Sec. 2003, 2020); “Advanced Reactor Demonstration Program,” Office of Nuclear Energy, accessed January 31, 2024, *https://www.energy.gov/ne/advanced-reactor-demonstration-program*.

84 “Civil Nuclear Credit Program,” Grid Deployment Office, accessed January 31, 2024, *https://www.energy.gov/gdo/civil-nuclear-credit-program*.

85 “Title 17 Clean Energy Financing,” Department of Energy Loan Programs Office, accessed May 28, 2024, *https://www.energy.gov/lpo/title-17-clean-energy-financing*.

86 “Advanced Nuclear Energy Projects,” Department of Energy Loan Programs Office, accessed May 28, 2024, *https://www.energy.gov/lpo/advanced-nuclear-energy-projects*.

87 “Optimizing Nuclear Waste and Advanced Reactor Disposal Systems,” Advanced Research Projects Agency-Energy, accessed January 31, 2024, *https://arpa-e.energy.gov/technologies/programs/onwards*.

88 “Converting UNF Radioisotopes Into Energy (CURIE),” Advanced Research Projects Agency-Energy, last modified March 15, 2022, *https://arpa-e.energy.gov/technologies/programs/curie*.

89 “Industrial Demonstrations Program,” Office of Clean Energy Demonstrations, accessed January 31, 2024, *https://www.energy.gov/oced/industrial-demonstrations-program*.

90 “26 U.S. Code § 45V - Credit for production of clean hydrogen,” Cornell Law School, accessed January 31, 2024, *https://www.law.cornell.edu/uscode/text/26/45V*.

91 Establishing a thriving hydrogen market will make nuclear cogeneration increasingly attractive. “Regional Clean Hydrogen Hubs Selections for Award Negotiations,” Office of Clean Energy Demonstrations, accessed January 31, 2024, *https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations*.

92 “Clean Hydrogen Electrolysis Program,” Office of Energy Efficiency & Renewable Energy, accessed January 31, 2024, *https://www.energy.gov/eere/clean-hydrogen-electrolysis-program*.

93 “Infrastructure and Jobs act: Carbon capture, utilization and storage investment ,” International Energy Agency, last modified May 25, 2023, *https://www.iea.org/policies/14982-infrastructure-and-jobs-act-carbon-capture-utilization-and-storage-investment*.

94 Nuclear Energy Innovation and Modernization Act, S.512, 115th Congress, (2019).

95 “Review of the Draft Proposed Part 53 Rule Language,” Breakthrough Institute, December 6, 2022, *https://thebreakthrough.imgix.net/Whitepaper-Review-of-draft-Part-53-package-Dec-2022-v2.pdf*.

96 U.S. Nuclear Regulatory Commission, “Staff Requirements – Secy-23-0021 – Proposed Rule: Risk-Informed, Technology-Inclusive Regulatory Framework For Advanced Reactors,” Memorandum (RIN 3150-AK31), March 4, 2024, *https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML24064A039*.

97 “Regulatory Review Roadmap For Non-Light Water Reactors,” U.S. Nuclear Regulatory Commission, last modified October 9, 2023, *https://www.nrc.gov/reactors/new-reactors/advanced/rulemaking-and-guidance/regulatory-review-roadmap-for-non-light-water-reac.html*.

98 Travis Chapman and Steve Vaughn, “Risk-Informed Performance-Based Licensing Basis: X-energy’s Approach to NEI 18-04 Implementation” (presentation at U.S. Nuclear Regulatory Commission Public Meeting, June 7, 2021), *https://www.nrc.gov/docs/ML2122/ML21221A043.pdf*.

99 “Industry-Led Licensing Modernization Project,” U.S. Nuclear Regulatory Commission, accessed January 31, 2024, *https://www.nrc.gov/reactors/new-reactors/advanced/modernizing/rulemaking-and-guidance/industry-led-licensing-modernization-project.html*.

100 Juli Kozeracki et al., Pathways to Commercial Liftoff: Advanced Nuclear (Washington, D.C.: Department of Energy, 2023), *https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf*.

101 Support for the existing fleet of nuclear power is outside the scope of this paper, but we recognize the importance of their continuation. It is necessary to support continued operation of existing nuclear units for as long as possible and support the investments necessary to complete subsequent license renewals to run reliably and safely for an additional 20 years. The nuclear 45U tax credit has provided a necessary lifeline to nuclear units, but that support ends in 2032 and many units, particularly in competitive markets, will be economically challenged at that time. If these reactors retire prematurely or fail to seek license extension, the workforce necessary to operate the next generation of nuclear units will be absent and the investment community will question the viability of nuclear projects.

102 U.S. Federal Register, “Section 45Y Clean Electricity Production Credit and Section 48E Clean Electricity Investment Credit,” Proposed Rules Vol. 89 No. 107, sec. 1.45Y-5[c][2] (June 3,2024), *https://www.govinfo.gov/content/pkg/FR-2024-06-03/pdf/2024-11719.pdf*.

103 “Onsite Energy Technical Assistance Partnerships (TAPS),” Better Buildings U.S. Department of Energy, accessed January 31, 2024, *https://betterbuildingssolutioncenter.energy.gov/onsite-energy/taps*.

104 Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act, S.1111, 118th Congress, (2024); U.S. Senate Committee on Environment & Public Works, “Senate Passes Bipartisan Nuclear Energy Bill from Capito, Carper, Whitehouse,” July 27, 2023, *https://www.epw.senate.gov/public/index.cfm/2023/7/senate-passes-bipartisan-nuclear-energy-bill-from-capito-carper-whitehouse#*.

105 “U.S. State Carbon Pricing Policies,” Center for Climate and Energy Solutions, last modified November 2023, *https://www.c2es.org/document/us-state-carbon-pricing-policies/*.

TABLE/BOX ENDNOTES

1 “BWRX-300 small modular reactor,” GE Hitachi Nuclear Energy, accessed January 31, 2024, *https://nuclear.gepower.com/bwrx-300*.

2 Office of Nuclear Energy, “First U.S. Small Modular Boiling Water Reactor Under Development,” February 19, 2020, *https://www.energy.gov/ne/articles/first-us-small-modular-boiling-water-reactor-under-development*.

3 “VOYGR Power Plants,” NuScale Power, accessed January 31, 2024, *https://www.nuscalepower.com/en/products/voygr-smr-plants*.

4 U.S. Office of Nuclear Energy, “NuScale Power and Metatomic Energy Awarded GAIN Vouchers to Advance Nuclear Technologies,” September 26, 2023, *https://www.energy.gov/ne/articles/nuscale-power-and-metatomic-energy-awarded-gain-vouchers-advance-nuclear-technologies*.

5 “Oklo,” Oklo, accessed January 31, 2024, *https://www.oklo.com/*.

6 U.S. Air Force, “Micro-reactor pilot program reaches major milestone,” August 31, 2023, *https://www.af.mil/News/Article-Display/Article/3512696/micro-reactor-pilot-program-reaches-major-milestone/*.

7 “Carbon-Free Power for the Clean Energy Transition,” Natrium TerraPower, accessed January 31, 2024, *https://natriumpower.com/*.

8 A coal-to-nuclear project is one that transitions a coal power plant site to a nuclear power plant site. This concept is further explored in this paper’s section on workforce. “TerraPower Purchases Land in Kemmerer, Wyoming for Natrium Reactor Demonstration Project,” TerraPower, August 16, 2023, *https://www.terrapower.com/terrapower-purchases-land-in-kemmerer-wyoming-for-natrium-reactor-demonstration-project/*.

9 U.S. Government Accountability Office, Nuclear Energy Projects, DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types (Washington, D.C.: U.S. GAO, 2022), *https://www.gao.gov/assets/gao-22-105394.pdf*.

10 “TerraPower awarded $8.5 Million in federal funding to research solutions for used fuel from advanced nuclear reactors,” TerraPower, March 14, 2022, *https://www.terrapower.com/arpa-e-terrapower-funding-waste/*.

11 “AP300 SMR,” Westinghouse Nuclear, accessed January 31, 2024, *https://www.westinghousenuclear.com/energy-systems/ap300-smr*.

12 Loan Programs Office, “How the Loan Programs Office and Plant Vogtle are Shaping the Energy Transition through Nuclear Technology,” October 28, 2022, *https://www.energy.gov/lpo/articles/how-loan-programs-office-and-plant-vogtle-are-shaping-energy-transition-through*.

13 “Xe-100: The Most Advanced Small Modular Reactor,” X-energy, accessed January 31, 2024, *https://x-energy.com/reactors/xe-100*.

14 Alan Charlish, “Poland approves construction of SMR nuclear units at six sites,” Reuters, December 7, 2023, *https://www.reuters.com/sustainability/climate-energy/poland-approves-construction-smr-nuclear-units-six-sites-2023-12-07/*.

15 “US companies sign up with Oklo for microreactor power,” World Nuclear News, April 9, 2024, *https://www.world-nuclear-news.org/Articles/US-companies-sign-up-with-Oklo-for-microreactor-po*.

16 “Triso-x Fuel,” X-energy.

17 “Xe-100 Technology Explainer,” X-energy, September 6, 2023, *https://x-energy.com/updates-all/technology-explainer*

18 Triso-x Fuel,” X-energy.

19 World Economic Forum, Transitioning Industrial Clusters towards Net Zero (Cologny, Switzerland: WEF, 2022), *https://netl.doe.gov/sites/default/files/netl-file/22CM_GS_Stark.pdf*.

20 One industrial cluster that plans to take advantage of proximity is the Humber Industrial Cluster in the UK. It is the highest-emitting industrial cluster in the UK, creating 30 percent higher emissions than the next largest. With such centralized emissions, there is a large opportunity for meaningful collaborative decarbonizing changes that will drive emissions reductions. Their decarbonization plan aims to reach net zero emissions by 2040, targeting their heaviest emitting sectors: steel and chemicals. “Together It Is Possible,” Humber Industrial Cluster Plan, accessed January 31, 2024, *https://www.humberindustrialclusterplan.org/*; “What is HICP?” Humber Industrial Cluster Plan, accessed January 31, 2024, *https://www.humberindustrialclusterplan.org/the-plan.html*.

21 Industrial clusters serve to minimize risk and cost for all facilities involved due to the shared burden of redundancy measures. Industrial facilities need to have an excess of heat and power to avoid unforeseen stoppages that lead to delays and losses. When using a nuclear reactor, the process cannot be turned on or off quickly to meet sudden demand, so redundant energy must be generated constantly, oftentimes meaning extra units must be installed. In an instance where an industrial cluster of five facilities might need power equal to ten nuclear units for overall baseline operating power (two units per facility), they can share the cost of redundancy by operating an additional two units for redundant power. This power would be available to a facility if a power shutdown were to occur at a fraction of the cost; the financial risk is lower when the cost is spread across facilities, rather than a single facility shouldering the cost of doubling their operating power to mitigate the risk of stoppages.

22 Bonus incentives for 45Y and 48E, both increased by 10 percent if located in an energy community, aim to promote the just transition of high-polluting fuel jobs to clean energy jobs. They may receive an additional 10 percent domestic content bonus. The base credits may be multiplied by 5 times if prevailing wage and apprenticeship requirements are met (in the case of 45U as well). “26 U.S, Code § 45Y - Clean electricity production credit,” Cornell Law School, accessed January 31, 2024, *https://www.law.cornell.edu/uscode/text/26/45Y*.

23 “26 U.S. Code § 48E - Clean electricity investment credit,” Cornell Law School, accessed January 31, 2024, *https://www.law.cornell.edu/uscode/text/26/48E*.

24 “26 U.S. Code § 45U - Zero-emission nuclear power production credit,” Cornell Law School, accessed January 31, 2024, *https://www.law.cornell.edu/uscode/text/26/45U*.

25 “26 U.S. Code § 45J - Credit for production from advanced nuclear power facilities,” Cornell Law School, accessed January 31, 2024, *https://www.law.cornell.edu/uscode/text/26/45J*.

26 “Federal Tax Incentives: Advanced Nuclear Production Tax Credit,” AndreTaxCo, PLLC, accessed January 31, 2024, https://www.andretaxco.com/adv-nuclear-production-credit.

27 Office of Nuclear Energy, “Inflation Reduction Act Keeps Momentum Building for Nuclear Power,” September 8, 2022, *https://www.energy.gov/ne/articles/inflation-reduction-act-keeps-momentum-building-nuclear-power*.

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The Center for Climate and Energy Solutions (C2ES) is an independent, nonpartisan, nonprofit organization working to secure a safe and stable climate by accelerating the global transition to net-zero greenhouse gas emissions and a thriving, just, and resilient economy.

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