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Energy and Industrial Use Cases for Advanced Nuclear Reactors

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Disclaimer

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Acronyms

AI	Artificial Intelligence
BWR	Boiling Water Reactor
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DoD	United States Department of Defense
DOE	United States Department of Energy
EOR	Enhanced Oil Recovery
EPZ	Emergency Planning Zone
FOAK	First-of-a-Kind Technology
GHG	Greenhouse Gas
HALEU	High-Assay Low-Enriched Uranium
HTGR	High-Temperature Gas Reactor
IAEA	International Atomic Energy Agency
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
NARUC	National Association of Regulatory Utility Commissioners
NPP	Nuclear Power Plant
PPA	Power Purchase Agreement
PWR	Pressurized Water Reactor
REE	Rare Earth Element
SMR	Small Modular Reactor

1. Introduction

Public Utility Commissions and State Energy Offices will play a vital role in supporting the development of advanced nuclear projects over the next decade. Understanding applications for advanced nuclear and identifying opportunities to connect the dots between state goals and potential projects will be critical in supporting these developments. As states consider the potential for advanced nuclear reactors, there is value in understanding advanced nuclear use case opportunities that are currently operating or being developed both in the United States and globally.

Already, several states have embarked on the process of considering how states can prepare for advanced reactors by developing reports and establishing working groups that provide state-level considerations related to advanced reactor technology development. These state activities highlight the importance of tracking advanced nuclear while also considering state-specific applications. For example, the Michigan Public Service Commission was tasked through Public Act 166 of 2022 with examining the feasibility of using nuclear generation as an alternative to provide reliable carbon-free power while Michigan transitions from fossil fuels. The final report released in March 2024, considers opportunities for potential applications of advanced reactors beyond electricity generation such as hydrogen production, district heating, desalination, direct air capture (DAC), and chemical/petroleum applications. The study further considered how these capabilities might align with other projects in Michigan, such as the Midwest Hydrogen Hub.[1]

Another example involving State Energy Office leadership can be found in Kentucky. The 2023 Senate Joint Resolution 79 directed the formation of the Kentucky Nuclear Energy Development Working Group, chaired by the Kentucky Office of Energy Policy and involving the Public Service Commission, electric utilities and cooperatives, the Tennessee Valley Authority, state legislators, National Laboratories, and other key stakeholders. The Working Group issued a report in November 2023 finding no "insurmountable barriers to nuclear energy development in Kentucky" while calling for local, state, and federal coordination on policy and regulatory actions to address challenges and unlock opportunities for beneficial nuclear energy development.[2] The report called for the creation of a Kentucky Nuclear Energy Development Authority to "support and facilitate the development of the nuclear energy ecosystem across the Commonwealth in a collaborative manner that enhances Kentucky's economy, offers opportunities that are safe, protects the environment across the Commonwealth, supports community voices especially in under-represented or historically impacted areas, increases energy education, and prepares a future workforce."[3]

These, and many other state actions, are a testament to states' interest in preparing for the potential of advanced nuclear. Various characteristics of advanced nuclear reactor technologies make them appealing for alternative use cases beyond traditional electricity generation. These characteristics include their safety profile, ability to produce high temperatures, flexible output, modular construction, smaller unit size, and ramping and black start capabilities.

The characteristics explored in **Table 1** demonstrate a number of the unique functions and abilities of advanced reactors, including the opportunities they provide to support other use cases. Developing alternative use cases for advanced reactors, especially where favorable circumstances exist for nuclear plants to generate electricity while at the same time providing additional services, a concept referred to as cogeneration, will help to unlock opportunities for continuous nuclear production during on- and off-peak hours.[4] In turn, these opportunities can support a stronger business case for advanced nuclear projects and provide additional revenues to enable first-of-a-kind (FOAK) and early development of advanced nuclear projects. These revenues can help to mitigate the costs of advanced nuclear projects for ratepayers and taxpayers. Opportunities for alternative use cases and cogeneration are explored further in *section 3*.

Table 1: Advanced Nuclear Characteristics

Characteristic	Overview
Safety profile	Advanced reactors have adopted significant advances in passive safety technology. Advanced reactors are designed to ensure that no off-site consequences occur (in case of emergencies) and can do so for an extended duration without requiring operator actions, power, or the addition of coolant.[A] Small modular reactors (SMRs) and microreactors also require smaller emergency planning zones than traditional nuclear reactors, which may allow construction in areas where traditional nuclear plants could not be located.
Potential to produce high temperatures	Unlike conventional light-water reactors, advanced reactors can provide process heat for industrial processes requiring high temperatures, many of which are difficult to decarbonize. Temperature ranges of heat application processes Liquid Metal Reactor[B] → Medium range (~500–600˚ C) High-Temperature Gas Reactor → High range (~750–950˚ C)* Gas-Cooled Fast Reactor → High range (~800˚ C) Molten Salt Reactor → High range (~800˚ C)[C]
Modular construction & configurability	Many advanced reactors are relatively small and designed for modular installation, which can allow the number of modules installed to be targeted to a site's power and heating needs. Multiple modular units at one site also offer greater coverage for planned outages (when individual units go offline for routine maintenance), while still providing power output.
Tailored size	Advanced reactor designs may range in size from large light water reactors (LWRs) (capable of producing ~1+ GW of power output) to SMRs (70–300 MW output) and microreactors (1–50 MW power output). A range of advanced reactor sizes allows project developers to right-size the reactor they select to the needs of a specific project.
Flexible ramping	Advanced reactors have greater variability to produce flexible ramping capabilities. That is, they are able to produce baseload energy or ramp up and down to meet demand. This allows these reactors to have additional flexibility in their output.
Flexible output	Heat is a necessary ingredient for many industrial chemical processes and a possible output for advanced reactors (in addition to electricity). The thermal energy generated by advanced reactors can be used to support an industrial process directly or indirectly (by producing steam or hydrogen). The potential of some advanced reactor designs to create high heat as an output unlocks new opportunities for use cases.
Black start capability	Black start is the ability of a power plant to restart parts of the power system to recover from a blackout.[D] Some advanced reactors are designed with the capability to start up from a completely de-energized state without receiving energy from the grid, which can support electric grid recovery from outages.[E]
Reliability	Advanced nuclear technologies have high capacity factors[F] and almost 24/7 operating capabilities that are not weather dependent. This means advanced nuclear technologies will receive capacity accreditation values close to their nameplate capacity, helping Load Serving Entities (utilities) meet their resource planning requirements.

* 750˚ C is the current output for near-term high-temperature gas reactors (HTGRs). Future designs are considering even higher heat targets such as 1000˚ C.

A José N. Reyes Jr., Finis Southworth, and Brian G. Woods, September 16, 2020, "Why the Unique Safety Features of Advanced Reactors Matter," The Bridge 50(3): 45–51, https://www.nae.edu/239255/Why-the-Unique-Safety-Features-of-Advanced-Reactors-Matter.

B For example, lead-cooled fast reactor and sodium-cooled fast reactor.

C World Nuclear Association, September 29, 2021, "Nuclear Process Heat for Industry," https://world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry.aspx.

D National Renewable Energy Laboratory, "Black Start," https://www.nrel.gov/grid/black-start.html#:~:text=Black%20start%20is%20the%20ability,form%20an%20interconnected%20system%20again.

E DOE Office of Nuclear Energy, July 2018, "5 Key Resilient Features of Small Modular Reactors," https://www.energy.gov/ne/articles/5-key-resilient-features-small-modular-reactors.

F The U.S. Energy Information Administration defines capacity factor as the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period.

This report provides a more detailed overview of potential alternative use cases for advanced nuclear and identifies considerations and key questions for state energy regulators and State Energy Offices.

2. Background

Since the first commercial nuclear energy power plant began generating electricity in 1957, the energy industry has utilized nuclear power to generate electricity for the power grid. In the United States today, there are two types of light water reactors (LWRs) in operation: boiling water reactors (BWR), where energy is produced by using heat created during atomic fission to boil water, producing pressurized steam, and pressurized water reactor (PWR), where water is heated to a very high temperature and kept under high pressure (to prevent water from boiling).[5] The resulting steam drives turbines, which activate generators to produce electrical power.[6] PWRs account for more than 65 percent of commercial reactors, and BWRs account for the remaining one-third of reactors in operation.[7]

Over time, nuclear technology has progressed, from Generation I (which includes early prototype reactors), to Generation II (which include the first commercial power plants), to Generation III (which provide improvements on Generation II such as fuel technology, thermal efficiency, and safety systems). Advanced nuclear reactors are generally agreed to comprise Generation III+ and Generation IV reactor technologies (reviewed in **Figure 1**). Generation III+ designs offer significant passive safety improvements over Generation III designs, and include a subcategory of reactors know as light water small modular reactors (SMRs) which generate less energy compared to traditional reactors (defined here as 300 MW or less), can be planned as modular units that can also be co-located together, and have smaller emergency planning zone[8] (EPZ) footprints.[9] Generation IV technologies continue to offer significant advances in passive safety features, while also utilizing alternatives to traditional fuel sources (e.g., high-assay low-enriched uranium (HALEU)) and alternative coolant methods (e.g., gas, metal, salt, etc.).[10]

Figure 1: Categories of Advanced Nuclear Reactors[11]

	Generation III+		Generation IV		
Reactor Type	Large Light Water Reactors	Light Water SMRs	High-Temperature Gas Reactors	Metal/Salt Cooled Reactors	Micro Reactors
Power Output	~1+ GW	~70–300 MW	~80–270 MW	~200–800 MW	~1–50 MW
Typical Fuel*	LEU	LEU	HALEU	HALEU	HALEU
Coolant	Water	Water	Gas, e.g., helium	Metal or salt	Various

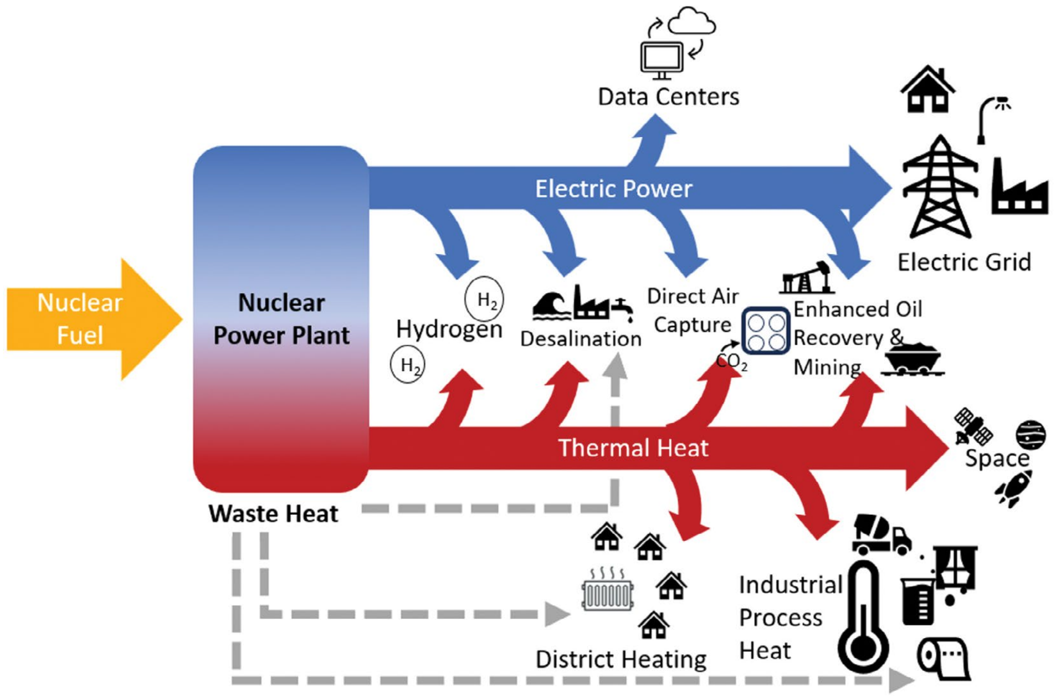
* The difference between low-enriched uranium (LEU) and high-assay low-enriched uranium (HALEU) is the percentage of the isotope Uranium-235 in the fuel, also known as enrichment. LEU is 3–5 percent Uranium-235, and HALEU is 5–20 percent Uranium-235.

3. Overview of Use Cases

Demand for nuclear energy is growing. Analysts project a more than 7 percent increase in load growth from data centers and electric vehicle charging by 2030.[12] At the same time, demands for the zero-carbon electricity and heat offered by nuclear reactors are projected to grow rapidly based on commercial demand and state support. Large commercial and industrial customers are continuing to set clean energy goals requiring clean power, such as the partnership between Google, Microsoft, and steel producer Nucor Corporation.[13] Several states including North Carolina, Virigina, New Jersey, Connecticut, and Michigan have started categorizing nuclear as a clean energy resource as part of a clean energy standard.[14] One example of this is Michigan's SB 271; the Clean Energy Future Bill which established a 100 percent clean energy standard for Michigan by 2040 and categorized nuclear as a clean energy resource. Finally, scientists are also considering the value of nuclear to fuel planetary space missions: nuclear thermal rocket engines could enable manned missions to Mars within the decade in a program from the National Aeronautics and Space Administration and Defense Advanced Research Projects Agency.[15]

Alternative use cases for advanced nuclear are being explored around the world and, in some cases, are already in use or part of demonstration or pilot projects. When considering alternative use cases for advanced reactors, it can be helpful to consider different possible nuclear power plant (NPP) outputs, as well as characteristics of different advanced reactor technologies and how these might shape potential output production. NPPs use fuel to produce electric power and thermal heat. These outputs can be used to create or support a variety of use cases, including desalination, hydrogen production, and industrial process heat. **Figure 2** provides an overview of thermal and electric outputs from nuclear.

Figure 2: Thermal and Electric Outputs from Nuclear



Author's construct based on diagram from the IAEA article, "Industrial Applications and Nuclear Cogeneration" (https://www.iaea.org/topics/non-electric-applications/industrial-applications-and-nuclear-cogeneration).

Cogeneration, the integration of NPPs with other systems and applications, is also an important consideration when mapping out advanced nuclear use cases. Heat generated by NPPs can be extracted at two different points for other applications, depending on whether the use case requires low-temperature or high-temperature heat. Low-temperature heat can be extracted from the steam turbine exhaust, after the turbine has generated electricity, while high-temperature heat can be used to drive a turbine for electric generation or to supply heat for industrial applications (e.g., steel, glass).[16] Heat can also be extracted between high- and low-pressure turbine stages.

All reactor types (Gen II, III, III+, and IV) can provide low-temperature post turbine steam, while advanced reactors (Gen III+ and IV) are also able to produce higher level temperatures than conventional reactors (Gen II and III).[17] In scenarios where a nuclear plant is able to produce electricity while heat generated by the power plant is also utilized, cogeneration has the potential to produce economic, environmental, and efficiency-related benefits via applications such as district heating, desalination, low- and high-temperature industrial processes, hydrogen production, and synthetic fuel production.[18] As an example, for nuclear desalination, cogeneration produces electricity and uses thermal waste heat concurrently to support desalination. However, it is important to note that the impact of cogeneration on an NPP's electricity output may differ depending on reactor type, fuel type, and temperature level.[19]

The next section provides an overview of use cases that tap additional outputs for advanced nuclear beyond central-station electricity generation, reviews the type of reactor needed to create the output, and lists other considerations related to each use case. These alternative use cases have been categorized by heat application needs into the following categories: distributed electric power applications, electricity and waste heat applications, and high-temperature process heat applications. Some alternative use cases for advanced nuclear are already in use or are part of demonstrations or pilot projects.

Some of the alternative use cases identified in the following section are capable of operating using existing Gen II and III reactor technology (desalination being one example of this). In scenarios where advanced reactor technologies are not necessary for an alternative use case, the use case profile identifies this fact, and includes examples and scenarios where advanced reactor technology might provide efficiency and economic benefits for future applications.

A. Distributed Electric Power Applications

The following alternative use cases in **Table 2** focus on electric power applications other than traditional centralized energy generation for the power grid. These use cases benefit from the proximity of the NPP to the end use, and the cases identified represent areas of fast growth for future energy demand or opportunities to decarbonize difficult-to-decarbonize sectors of the economy by replacing fossil fuels with carbon-free energy production.

Data Centers

The rise of artificial intelligence (AI) has catalyzed a new wave of investments in data centers. Experts predict that the use of data centers for AI computing could require more than five times the power of traditional data center facilities in order to support the higher processing requirements for data centers to run deep learning models.[20] This is expected to translate into a doubling of data center power consumption between 2022 and 2030 from 17 GW to 35 GW.[21] To meet this energy demand, many companies are exploring new sources of nuclear power (see **Figure 3**). Nuclear energy has the advantage of continuously producing reliable, carbon-free, baseload electricity; it is valuable for companies with high reliability needs and clean energy goals. Advanced reactors could be sized and sited to match load from data centers.

There is growing interest in co-locating large industrial facilities such as data centers with NPPs in restructured markets. This co-location model reduces the burden on the transmission system (and reduces lead time for grid interconnection by opting out) and can offer a reliable source of power to the off taker which can, in turn, offer greater price stability for the power plant generator.[22, 23]

Table 2: Distributed Electric Applications Overview

	Small Modular Reactors	Microreactors	
Use case	**Data centers** Data centers have high standards for reliability and power quality, which could be met through the use of SMRs to produce electricity for powering data centers and for cooling purposes.	**Resource extraction** Enhanced oil recovery (EOR) or mining operations plan to utilize microreactors. These types of technology could be deployed to remote oil fields or mining locations via truck bed.	**National defense** Eielson Air Force Base in Alaska is expected to pilot a microreactor. The Air Force pilot program aims to have an operational microreactor by 2027 to deliver electricity and steam to the base via a power purchase agreement (PPA). The base will provide a land lease to a third party that will own and operate the reactor.[24] The Department of Defense's (DoD) Strategic Capabilities Office is overseeing Project Pele, which aims to design, build, and demonstrate a mobile reactor within five years producing 1–5 MW of electrical power.[25]
Technology readiness	SMRs have been deployed in other countries, but not yet in the United States. However, advanced reactor developers in the United States report interest from data center customers.	DOE supports research and development efforts for a variety of microreactor designs including gas, liquid metal, molten salt, and heat pipe-cooled concepts.[26] DOE's planned microreactor test platform, MARVEL (a sodium-potassium-cooled microreactor which will generate 85 kW of thermal energy) is expected to be completed at Idaho National Laboratory's Transient Reactor Test Facility by 2027.[27] As of August 2023, testing for the Project Pele microreactor is expected to begin at Idaho National Laboratory in 2026.[28]	
Active cases or pilots?	Standard Power announced plans in 2022 to build two NuScale SMRs in Ohio and Pennsylvania to provide 2 GW of SMR generation to power two new data centers by 2029.[29] Green Energy Partners (see Figure 3).	The state of Wyoming awarded $10 million in funding to BWXT in 2023 to assess microreactor deployment and applications.[30]	DOE's MARVEL and DoD's Project Pele microreactors are expected to be completed in 2027 and 2026 respectively, with other private microreactor developers eyeing deployment in the early 2030s. Project Pele's goal is to support the DoD's goal of developing a transportable power source.

Figure 3: Green Energy Partners Data Center

Green Energy Partners LLC of Virginia has secured 641 acres of land in Surry County, Virginia, where it plans to create a fully integrated Green Energy Center. This project will include the development of 1 GW of data centers, a green hydrogen hub, and deploying four to six SMRs to support the center's energy needs. In citing the need for this project, Green Energy Partners notes that data centers in Loudoun County, Virginia, use about 20 percent of Virginia's power capacity while supporting approximately 70 percent of the world's data traffic.

Green Energy Partners LLC, April 12, 2023, "Introducing the Nation's First Green Integrated Energy Center," PR Newswire, https://www.prnewswire.com/news-releases/introducing-the-nations-first-green-integrated-energy-center-301795477.html.

Resource Extraction

Oil and gas production, transportation, and processing account for approximately 15 percent of total greenhouse gas (GHG) emissions globally.[31] The potential to power upstream oil and gas facilities with nuclear provides an opportunity to cut emissions from the sector. Using nuclear for enhanced oil recovery (EOR) could entail utilizing energy in the form of steam, electricity, or direct fired heat from microreactors to replace current diesel generators used in EOR operations.[32,33] EOR and mining operations are well suited for microreactor deployment due to the remote locations of these operations and potential for extreme climates, which makes alternative forms of zero-emissions energy difficult to implement.

Mining is estimated to account for between 4 and 7 percent of worldwide GHG emissions but is essential for reducing GHG emissions as well. Rare earth elements (REEs) such as lithium and cobalt are necessary in the production of batteries, wind turbines, solar panels, nuclear reactors, and other technologies. Distributed microreactors have the potential to dramatically change the GHG footprint of mining because these reactors could provide the heat and electricity needed to meet the high energy requirements of ore processing. Additionally, there is a unique opportunity for advanced reactors in mining as mining operations may be too remote to connect with an electric grid.[34] Wyoming is actively exploring the deployment of the BWXT[35] high-temperature gas reactor (HTGR) to support the state's extraction industry with $10 million of funding from the Governor's Energy Matching Funds program.[36,37]

National Defense

The U.S. Department of Defense (DoD) has expressed interest in both stationary and mobile microreactors for use at military installations and conflict zones. Stationary reactors could be sized to support the high reliability and resilience needs of military bases. At permanent installations, energy resources should provide for at least 14 days of fuel disruption,[38] requiring the use of natural gas or diesel generators with on-site fuel storage or reliable transportation, renewable wind and solar power with battery backups, or advanced nuclear reactors. Nuclear reactors may be particularly attractive for remote locations with mission-critical activities.[39] The deployment of advanced reactors to serve these loads could reduce the need for distribution and transmission investments to reach remote locations. Mobile reactors could be deployed to warfighting locations and serve humanitarian and disaster recovery efforts.[40] Defense facilities can also partner with state regulators and State Energy Offices to collaborate on planning and funding projects that benefit the military, customers, and taxpayers.[41]

Distributed Electric Power Application Considerations for Public Utility Commissions and State Energy Offices

- What are the growth projections for large commercial and industrial customers and how are utilities planning to meet expected load growth?
- What are the expectations for future resource capacity values for existing and planned new resources, and how do those compare to advanced nuclear?
- Are there opportunities for large off-takers, such as data centers, to enter into PPAs to help fund early advanced nuclear projects?
- How will behind-the-meter co-location arrangements impact customer rates?
- What is the process for siting advanced reactors, such as SMRs and microreactors?
- Will SMRs and micro reactors require external power sources for instrumentation during start-up and operations?
- How can state agencies engage with reactor projects to ensure safety and environmental regulations are being followed wherever they are located?
- How can state agencies coordinate with the Nuclear Regulatory Commission to provide input on regulations impacting advanced reactor deployment and site-specific licensing and environmental reviews?
- How will stakeholder engagement differ for distributed SMRs or microreactors versus traditional nuclear projects?

B. Electricity and Waste Heat Applications

Low-temperature heat applications or use cases that can utilize either low process heat or electric power to support use cases present valuable opportunities to reduce costs and emissions and are reviewed in **Table 3**. Unlike the next section on high-temperature heat applications, many of these use cases are able to utilize existing nuclear reactor technology. However, these use cases still present opportunities for advanced reactor technologies to improve efficiency, or scale more effectively, to support these applications.

Table 3: Low Process Heat or Electric Power Applications

	District Heating	Desalination	Direct Air Capture (DAC)
Use case	District heating relies on waste heat from the NPP, so LWR technology provides adequate heat for this application, although advanced reactors could also be used for cogeneration.	Desalination plants in operation today use PWR technologies to support the desalination process. SMR designs could also be utilized, as electricity or process heat can both support desalination. SMRs may be easier to finance than conventional reactors.	DAC is possible with different reactor technologies. The process depends on whether the DAC project is utilizing steam flow, energy produced, or both and can potentially utilize pressurized water reactors, sodium-cooled fast reactors, or HTGRs.[42] Advanced reactors can be sized and sited specifically to support DAC loads.
Technology readiness	Currently in use. Nuclear power was first used for district heating in Bulgaria in 1988.[43] The first application of district heating with a Gen III+ NPP was in 2019 (see Figure 4).	This is a mature technology and has been in use since the 1970s with conventional (Gen III) reactors.	DAC is still in pilot and demonstration project phases.
Active cases or pilots?	Steady Energy, a spin off from the VTT Technical Research Centre in Finland announced in February 2020 the launch of a project to develop an SMR for district heating. Steady Energy proposes the construction of its LDR-50 SMR by 2030.[44] Illinois Microreactor Demonstration Project at University of Illinois Urbana-Champaign in collaboration with Ultra Safe Nuclear Company[45]	South Korea has developed a SMR design for cogeneration of electricity and desalination, the 330 MW SMART reactor is coupled with four multi-effect distillation units. Saudi Arabia established a cooperation agreement in 2017 with China Nuclear Engineering and Construction Group to establish a partnership project for desalination using HTGRs.[46]	Sizewell C nuclear facility DAC demonstration project.[47] Byron Nuclear Plant DAC study is currently underway in Illinois (see Figure 6). CarbonCapture, the lead developer on the carbon removal proposal associated with the Wyoming Regional Direct Air Capture Hub, has indicated an interest in considering SMR use in its Wyoming DAC Hub plan.[48]

District Heating

District heating utilizes an underground infrastructure asset to distribute thermal energy to multiple buildings from a central energy plant, where steam or hot water produced at the plant is transmitted via piping networks to local buildings' heating systems to avoid the need for boilers in individual buildings.[49] District heating is a cogeneration biproduct—in this model, a NPP still produces electricity as its primary product, and district heat is also produced using waste heat (see **Figure 4**). Nuclear district heating systems have the potential to replace individual heating boilers, eliminating emissions from each individual unit. Nuclear heat in the form of hot water or steam can be economically delivered up to 100 miles away at competitive costs with minimal heat loss.[50]

Figure 4: Akademik Lomonosov and Haiyang NPP, District Heating Use Cases

Akademik Lomonosov, the world's first commercial floating nuclear combined heat and power plant began supplying 70 MW of space heating and domestic hot water to the Russian port city of Pevek on the East Siberian Sea. The plant utilizes two KLT-40S reactors (each producing 35 MW) and was connected to the power grid in December 2019. It is expected to generate enough power to serve about 200,000 people for an initial lifespan of 40 years, with potential extensions.[51, 52] Floating NPPs can be built in a factory, assembled in a shipyard, and transported to a site. These characteristics are expected to help reduce construction timelines and keep costs down when compared to traditional NPP construction methods.[53]

Haiyang NPP consists of two AP1000 units, which produce 2.5 GW of energy (1,250 MW per unit) located in the Shandong Province of China. This nuclear heating demonstration project commenced operations in November 2019 and initially provided heat to 700,000 square meters of housing near the plant. The phase two expansion of this project began service in November 2021 and expanded the heat supply area to 5.2 million square meters, supplying heat to the entire city of Haiyang, which consists of approximately 200,000 residents. The waste heat captured from the steam output of Haiyang NPP is sent to an off-site heat exchange station, and from there, it is transferred to residential homes through a municipal heating pipeline network. Haiyang nuclear energy heating project replaced as many as 12 local coal-fired boilers.[54, 55]

Desalination

Utilizing nuclear energy for desalination is not a new concept—India and Kazakhstan began desalinating water using nuclear energy in the 1970s. The desalination process is energy-intensive, requiring large numbers of pumps to achieve the high pressure required to separate salts and dissolved solids from seawater.[56] Two major types of desalination technologies can be classified as thermal processes (feedwater is boiled and the vapor is condensed as distilled water), or membrane desalination (feedwater is pumped through semi-permeable membranes to filter out dissolved solids). The major technology being built today is reverse osmosis; a membrane desalination process in which electric pumps pressurize water and force it through a semi-permeable membrane. In 2016, 73 percent of desalination projects in the world utilized membrane desalination techniques, while the other 27 percent of projects utilized thermal desalination.

Figure 5: Rostov NPP, Desalination Use Case

Rostov NPP, located in Volgodonsk, Russia, produces desalinated water using eight multi-effect distillation plants that use a low-temperature thermal process for capturing fresh water by recovering the vapor of boiling seawater. Rostov NPP has been producing fresh water through this process since 2010, using a water-water energetic reactor (or VVER) with a net capacity of 950 MW.

Small- and medium-sized nuclear reactors can support desalination activities, often while supporting electricity cogeneration using low-pressure steam from the turbine and hot seawater fed from the final cooling system (see **Figure 5**). Desalination also provides an opportunity to continually operate nuclear plants at full power by supplying the grid during high-energy demand times, and then utilizing surplus power to desalination plants during off-peak periods.[57] While desalination projects have successfully used Gen III technology, new concepts are being developed that apply advanced reactor designs to desalination activities to improve process efficiency.

Direct Air Capture (DAC)

The United Nations Intergovernmental Panel on Climate Change has identified large-scale deployment of carbon dioxide (CO_2) removal technologies as necessary to meet net zero targets.[58] DAC is one of the most mature carbon removal technologies available, but the systems require heat to drive chemical reactions to remove CO_2 from the air and electricity to power the equipment.[59] Nuclear can assist in DAC projects that remove CO_2 directly from the atmosphere using several techniques (see **Figure 6**).

A 2023 DOE report—Assessment of Nuclear Energy to Support Negative Emission Technology—found that NPPs were compatible with DAC systems and identified the following potential benefits of coupling NPPs with DAC: large amounts of decarbonized and constant-output electricity; free waste heat or cheap low-temperature heat; or high-temperature heat. The report also determined that using nuclear power for DAC could reduce the levelized cost of solid, sorbent-based DAC systems by about 13 percent and liquid, solvent-based DAC systems by about 7 percent when compared with the costs of nonnuclear DAC systems.[60]

Figure 6: Byron Nuclear Power Plant and Sizewell C, Direct Air Capture Use Cases

Byron Nuclear Plant Direct Air Capture Study. Constellation, Carbon Engineering, Worley Group Inc., Pacific Northwest National Laboratory, and the University of Illinois Urbana-Champaign are participating in a DOE-funded study of DAC technology at Constellation's Byron Nuclear Generating Station in northern Illinois. Byron Nuclear Generating Station was commissioned in 1985 and consists of two Westinghouse pressurized water reactors. The proposed study would add a chemical solution to water flowing through the facility's condenser on the nonnuclear side of the plant. After traveling through the condenser, the water would travel out to the cooling towers, where CO_2 would attach itself to the chemical solution and be captured and sequestered.[61]

Sizewell C and Associated British Ports plan to build a demonstration project utilizing nuclear for DAC in partnership with Nottingham and Birmingham Universities and engineering firms Helical, Atkins, and Altrad Babcock.[62] The Sizewell C demonstration plans to use heat-powered DAC technology and up to 400 megawatt thermal of waste heat from the NPP to capture 1.68 million tons of CO_2 per year.[63] If the initial demonstration project is successful, a permanent, full-scale DAC system at the Sizewell C Nuclear Power Station would be installed to operate without significant impact on the power station's electricity output.[64] Sizewell C is projected to be fully operational by 2034.[65]

Electricity and Waste Heat Application Considerations for Public Utility Commissions and State Energy Offices

- Are there opportunities for existing NPPs to run continuously at full capacity by adopting a cogeneration approach where electricity is used to meet grid load and applied to industrial uses, with proportions changing to meet the load profiles of electricity and industrial users?
- Do existing regulations hinder new business models to enable cogeneration?
- With the ability of advanced reactors to produce electricity and heat, what are the siting, sizing, and operational considerations for these reactors to support district heating, desalination, and DAC demands?
- Can end users partner with other electric or heat loads to aggregate demand for new nuclear generation?
- How can states ensure the availability of heat and power to end uses while prioritizing reliability and affordability for existing customers?
- What would the process look like to retrofit an existing NPP to provide district heat? What investments and/or reconfigurations would be required?
- How can states participate in planning cogeneration projects to look for opportunities to advance state policy goals?

C. High-Temperature Process Heat Applications

High-temperature process heat is necessary for the production of materials such as chemicals, steel, and hydrogen. High-temperature reactors are Gen IV reactors, which utilize TRISO fuels and are capable of reaching higher temperatures (between 700° C and 950° C) and maintaining temperatures precisely. This can reduce the margin of error for operators leading to cost efficiency. High-temperature reactors (such as High-Temperature Gas Reactors, Molten Salt Reactors, and Gas Cooled fast reactors) are also capable of thermal energy storage and providing flexible, load-following capabilities, which allows these reactors to support intermittent renewable energy resources. These applications are reviewed in **Table 4**.[66]

The Congressional Budget Office estimates that 17 percent of GHGs are produced as a result of heat supplied to manufacturing and other industrial processes.[67] Use of nuclear to provide this process heat can be, therefore, an important element in reducing CO_2 emissions.[68] Globally, industrial activity was directly responsible for 9.4 gigatons (Gt) of CO_2, accounting for 25 to 30 percent of global emissions in 2021.[69] Developing opportunities for carbon-free energy sources, such as advanced nuclear reactors, is critical to reducing industry emissions.

Utilizing advanced nuclear generation to support production of chemical, glass, cement manufacturing, and metal production offers a promising opportunity to reduce emissions in this difficult-to-abate sector of the economy. While current LWRs are capable of producing heat up to 300˚ C (adequate for district heating and seawater desalination purposes), newer concepts for advanced nuclear use rely on the high heat output promised by Gen IV nuclear technologies to provide heat for difficult-to-decarbonize industries currently powered by fossil fuels. Specifically, these applications require high-temperature gas reactors, gas-cooled fast reactor, or molten salt reactor technologies to produce the process heating needed for these applications to have reduced GHG footprints. **Figure 8** provides an overview of the temperature ranges required for specific heat application processes and the types of NPPs that produce heat within these ranges.

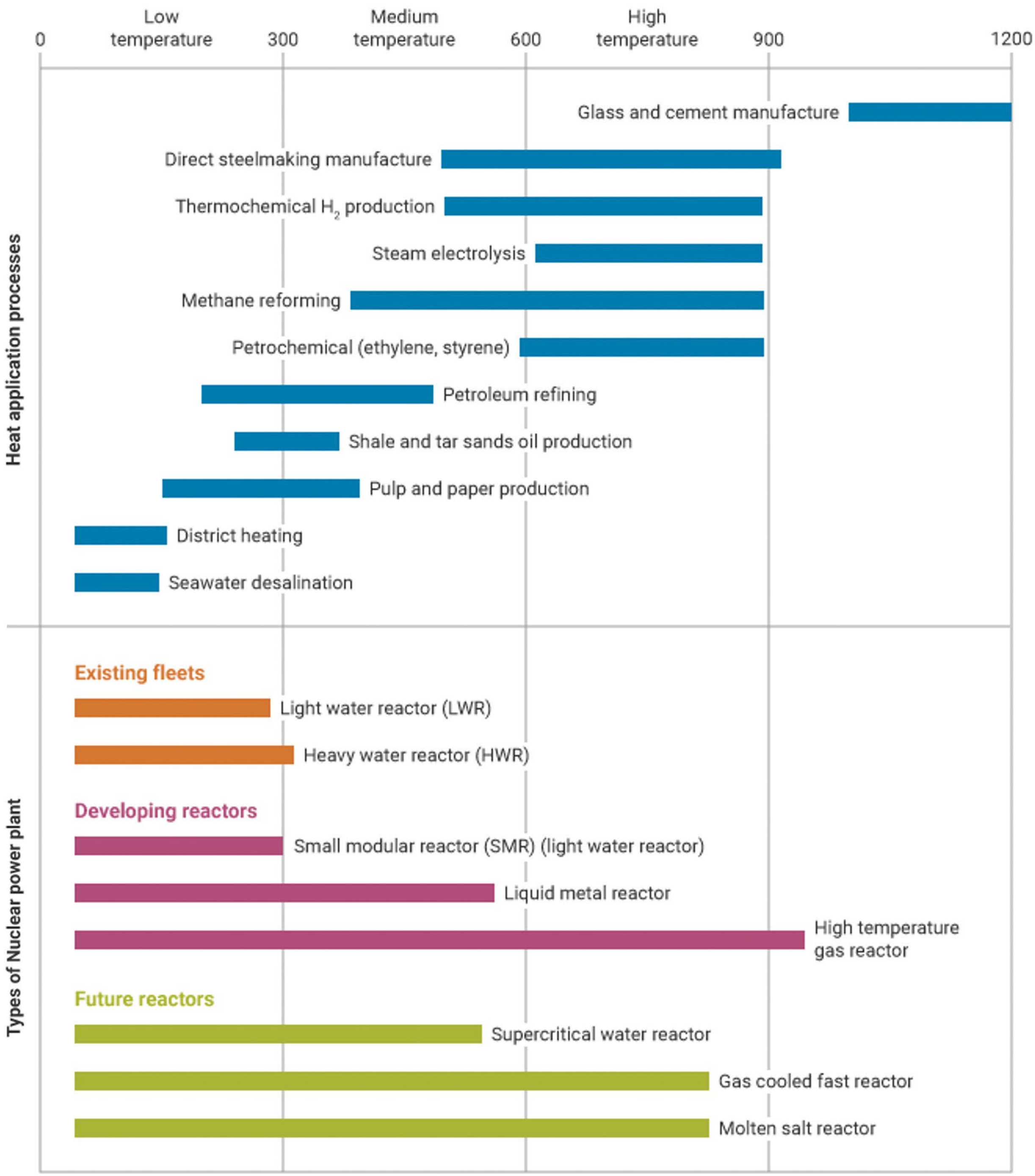
Table 4: High-Temperature Process Heat Applications

	Chemical Applications	Steel, Glass, and Cement	Hydrogen
Use case	Gen IV Chemical production requires high temperatures (in the range of 600–900° C). Currently, HTGRs are the only type of reactor that produce high enough temperatures for these heat applications.	Gen IV Steel production requires production of high temperatures (in the range of 600–900° C). Glass and cement production requires production of higher temperatures (1000–1200° C range).	Reactor technology is dependent on the preferred method of hydrogen production. Conventional electrolysis requires electricity (available through Gen III reactors) while hydrogen production through thermochemical cycles may require high-temperature heat (available through Gen IV technologies).
Technology readiness	Requires the use of Gen IV technology based on previous HTGR technology.	Requires the use of HTGRs; these are Gen IV technology based on previous HTGR technology.[70]	Conventional electrolysis production of hydrogen is possible using existing LWR technology, while thermos- chemical cycle production would require advanced reactor technology not yet commercially available in the United States.
Any active cases or pilots?	Dow Chemical and X-energy Demonstration Project (see Figure 7).	Nucor and Helion announced plans to develop a 500 MW fusion power plant to power a steelmaking facility in the 2030s.[71]	Constellation Energy's Nine Mile Point Nuclear Plant in Oswego, New York. Vistra's David-Besse Nuclear Plant in Ottawa County, Ohio Xcel Energy's Prairie Island Nuclear Plant in Red Wing, Minnesota.
	Abilene Christian University's Nuclear Energy eXperimental Testing (NEXT) Lab has partnered with the NEXT Research Alliance to design, build, and operate a molten-salt cooled, liquid-fueled research reactor at Abilene Christian University.[72] Molten salt reactors are advanced reactors that are able to produce the high temperatures required for industrial applications. While Oak Ridge National Laboratory ran a Molten-Salt Reactor Program from 1958 to 1976, and other countries have since started their own molten salt reactor research and development activities, this technology has not yet reached the commercialization stage.[73, 74]		

Figure 7: Dow Chemical and X-energy Demonstration

Dow Chemical and X-energy have formed a partnership to develop and deploy an advanced reactor to reduce emissions at one of Dow's manufacturing facilities in Texas. The project envisions a four-unit 320-MWe Xe-100 advanced nuclear reactor facility located at Dow's Seadrift site in Texas to support Dow's production of basic and specialty chemicals. These HTGRs will be able to provide both power and steam heat for Dow's industrial production facility. Dow and X-energy must submit a construction permit application to the Nuclear Regulatory Commission for review and approval before construction is expected to begin in 2026.[75] Dow cites the reliability of nuclear energy and the modularity of SMR units (allowing maintenance to occur while other units remain active) as key reasons for the decision to partner with X-energy to use SMRs for this emissions reduction project.[76, 77]

Figure 8: Temperature Ranges of Heat Application Processes and Types of NPPs[78]



Synthetic Fuels and Hydrogen

Synthetic fuels are alternatives for traditional liquified fossil fuels such as gasoline, diesel, and kerosene. They have the potential to significantly reduce the carbon footprint of the transportation industry if these synthetic fuels are produced using carbon-free sources, such as nuclear. Synthetic fuels have the same energy density as fossil fuels and differ from biofuels in that they do not require organic waste feedstocks to provide carbon and hydrogen inputs for fuel production. Synthetic fuels are seen as particularly important for decarbonizing transport sectors such as aviation and shipping, which require high power output and large on-board energy stores to support long-distance travel between fueling.[79] Synthetic fuels and hydrogen are also viewed as an opportunity to reduce emissions across hard-to-abate sectors of the economy such as transportation and industry, which accounted for over half of GHG emissions in 2021.[80] Hydrogen has the potential to fuel cars, heavy trucking, aviation, and shipping.[81]

Current hydrogen production methods include steam methane reforming, which commonly uses natural gas as a feedstock, and electrolysis, which uses electricity as an input. Producing hydrogen with electrolysis or thermochemical processes utilizing carbon-free energy sources (e.g., nuclear energy or natural gas-powered steam methane reforming with full carbon capture) will limit emissions (see **Figure 9**). When contemplating producing hydrogen with nuclear power, the process depends on the type of NPP under consideration. Some hydrogen production technologies (conventional electrolysis) require only electricity, while other, less mature technologies (thermochemical cycles) may require process heat at high temperatures. Hybrid technologies may require both electricity and high temperature steam (high-temperature steam electrolysis).[82]

Figure 9: Nuclear for Hydrogen Pilots and Future Applications

Constellation's Nine Mile Point Nuclear Station (General Electric BWR units) located in Oswego, New York, became the first NPP to produce hydrogen in March 2023, at its 1-MW demonstration scale production facility. DOE supported this project with an award of $5.8 million, which allowed for the construction and installation of an electrolyzer system. The New York State Energy Research and Development Authority also provided funding to support the plant's hydrogen long-duration storage component.

The Midwest Alliance for Clean Hydrogen (MachH2) Hydrogen Hub was selected to receive funding as part of the Bipartisan Infrastructure Law's $7 billion Regional Hydrogen Hub program. Part of the plan for this hub is to produce hydrogen using nuclear energy. Constellation announced plans in October 2023 to use a portion of its federal funding for the Midwest Hydrogen Hub (MachH2) to build a nuclear-powered clean hydrogen facility at its 2.3 GW LaSalle Clean Energy Center in Illinois.[83] The Michigan Feasibility Study Report draft released in January 2024, considers the impacts of nuclear for hydrogen being produced through this hub, and identifies potential uses within the state.[84]

High-Temperature Process Heat Application Considerations for Public Utility Commissions and State Energy Offices

- What information needs to be learned from pilot demonstrations to support decision making about future advanced reactor investments?
- How can states support efforts to cultivate a skilled workforce prepared to build, operate, maintain, and regulate advanced reactors for hydrogen and chemical applications?
- How can the federal government, states, and private corporations coordinate to support the development of business models and incentives to overcome barriers to the deployment of advanced reactors for high-temperature process heat?
- Are there differences in advanced nuclear waste profiles compared to the waste produced from traditional nuclear fuel sources?
- How will decommissioning and waste storage practices differ for distributed electric applications compared to traditional nuclear power plants?

4. Conclusion

Alternative use cases for advanced nuclear technologies have the potential to support some of the most pressing issues of our time by providing zero-carbon electricity of activities such as data centers, EOR, mining operations, district heating, desalination, DAC, industrial applications, and synthetic fuel production, which can support decarbonization of transportation sectors.

Developing alternative use cases for advanced reactors, especially where opportunities for cogeneration exist, present the potential to help unlock opportunities for continuous nuclear production during on-peak and off-peak hours, which will help to create a stronger business case for advanced nuclear projects and provide additional financial incentives to support early development of advanced nuclear projects.

Public Utility Commissions and State Energy Offices will play a vital role in supporting the development of advanced nuclear projects slated to begin in the next decade, so understanding potential use cases, identifying opportunities to connect the dots between larger state goals and initiatives, and considering potential challenges which might arise as advanced reactors begin construction phases will be critical in supporting these developments.

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