WHITE PAPER

Nuclear Microreactors Could Be Zero-Carbon Solution for Campus District Energy Systems

By Kevin Fox

Nuclear energy is emerging as a promising solution to the challenge of decarbonizing fossil fuel-based district energy systems, while preserving the reliability and resilience these systems have long been known for. Now with more than a dozen different designs in various stages of development, advanced microreactor technologies are attracting attention due to the potential to deliver scalable solutions for district energy applications.

Climate change presents one of the more pressing global issues of our time, and reducing carbon emissions is widely accepted as a key tactic for tackling this challenge. Achieving carbon reduction goals will require extensive planning, cooperation, investment and leadership among corporations, governments, institutions and society at large.

It is estimated that 42% of emissions are attributed to the construction and operation of buildings. Universities are among those under increasing pressure to decarbonize, and utility systems serving university buildings represent a significant source of campus carbon emissions.

For decades, district energy has been a trusted and reliable backbone for providing utilities in a campus setting (see Figure 1) but selecting and assembling a set of low- and no-carbon technologies that provide resilience and operational continuity is challenging. However, the energy transition is presenting opportunities for forward-thinking institutions to exert leadership and demonstrate the features and benefits emerging technologies can offer as new energy sources to reduce or nearly eliminate campus carbon emissions.

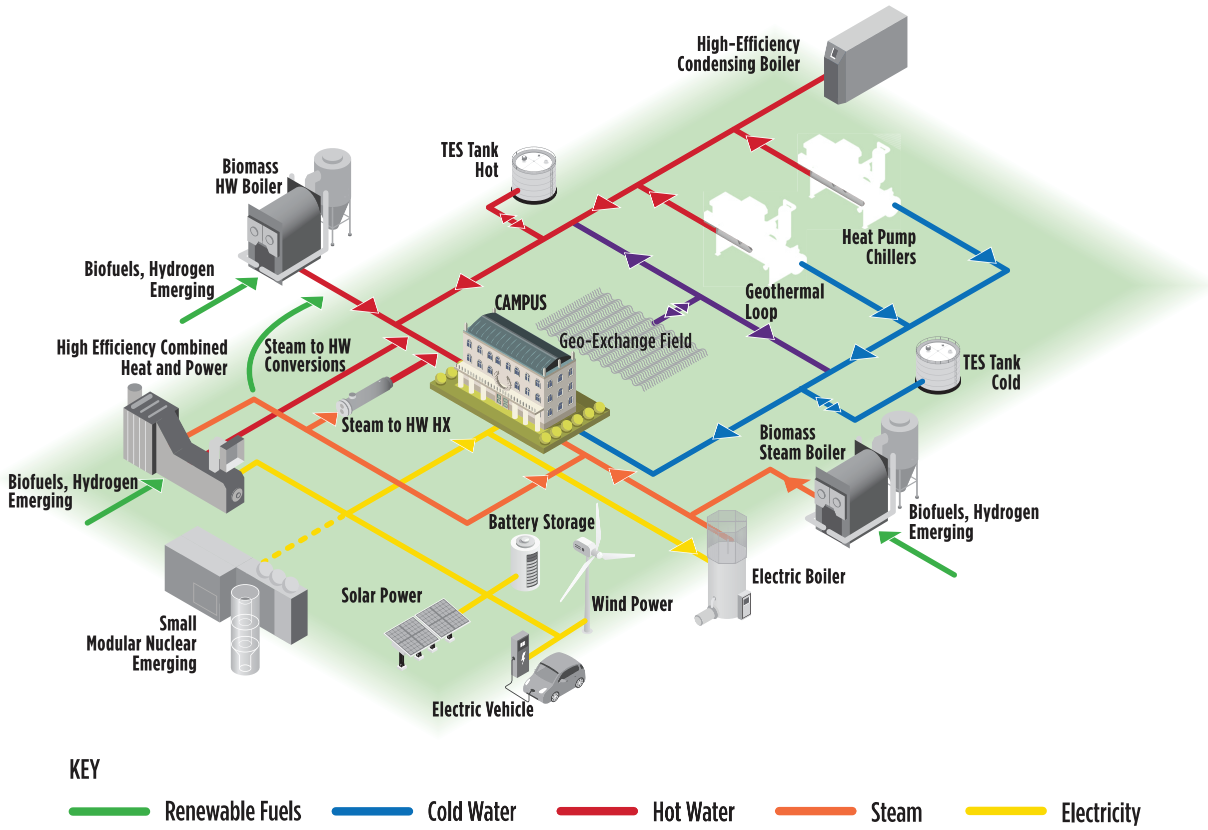

***Figure 1:** A district energy system can provide utilities in a campus setting.*

Microreactor Technology Pathways

When most of the public thinks about nuclear power, the images that typically come to mind are those of the traditional utility-scale reactors providing enormous supplies of baseload power. With total plant capacities often exceeding 2,000 megawatts (MW), many conventional light-water reactors have been in service for decades, providing clean and highly reliable power.

Under current Nuclear Regulatory Commission (NRC) definitions, small modular nuclear reactors are those with electrical generating capacity of 300 MW or less, while microreactors are those capable of producing no greater than 50 MW. There are now more than a dozen advanced nuclear reactors under development, with most fitting in these small to micro categories.

High-temperature gas-cooled reactor (HTGR) designs utilizing carbon dioxide, helium or nitrogen as the primary cooling agent are among the most common microreactor technologies under development. The design concept is to circulate gas through the nuclear core, keeping temperatures within stable ranges and using the gas as the agent to transfer heat to a steam generator that could then provide process steam for district energy applications or supply a turbine to generate electrical power.

Another type of advanced microreactor design uses molten salt as a coolant. Once heated to a liquefied state, the salt can cool a solid stationary fuel or may be combined with uranium-235 (U-235) or similar fissile material to form a liquid nuclear fuel.

Other microreactor design concepts include cooling by liquid metals — usually lead or sodium — in a concept that is called a fast reactor because such microreactors can operate using higher numbers of energy neutrons (fast neutrons) to sustain the fission chain reaction, compared with the thermal neutrons used in the core of conventional reactors.

A final major microreactor type is called a heat pipe, which makes use of the phase change of the working fluid and transfers heat from the evaporator to the condenser end of the reactor vessel with only a minuscule temperature drop. The heat pipe design makes use of liquid sodium (molten salt) coolant that is enclosed within the heat pipe, and the condenser heat is transferred to produce steam for the district system or for power generation.

A major advantage of microreactors is their ability for dispatchability and deployment. Several microreactor designs are portable and can be transported to a site via truck within a secure shipping container. Though the reactor and heat transfer systems are mobile and are suitable for safe siting in populated areas, they would need to be installed in a shielded, secure enclosure that would likely include several shipping-container-sized modules housing power generation, shielding, and control and safety systems inside a secured perimeter.

No Tolerance for Disruption

District energy system operators have long worked under the pressure of having zero tolerance for disruptions to supplies of steam, chilled water or power. When considering advanced nuclear technology for district energy systems, resilience ranks at the top of the list of benefits. Other benefits offered by advanced nuclear include (in no particular order):

- Zero carbon emissions during operation
- High-quality thermal energy source
- Compact footprint
- Ready integration with campus utilities
- Fit with academic mission
- Aesthetics

Though many large district energy systems — such as those serving airports or medical center complexes — could readily incorporate advanced nuclear technology, universities are uniquely suited to serve as the initial proving ground. Advanced nuclear checks all the boxes for universities because it can deliver abundant high-quality thermal energy in combination with carbon-free electricity. Also of importance, a microreactor may dovetail with the academic mission of teaching and research universities.

Microreactor technology is fundamentally different from conventional light-water reactor nuclear technology in commercial operation today. The reactors are designed with passive safety features that require no operator action to achieve safe shutdown, meaning the systems simply can't melt down. For example, a design pathway incorporating coated tri-structural isotropic (TRISO) fuel for HTGRs can withstand temperatures four times greater than fuel temperatures within conventional nuclear reactors, and thus is nearly impervious to meltdown.

The technologies also are modular, meaning they can be housed within an enclosed container with sufficient shielding to enable safe transport to a site via truck.

The key question going forward is how to properly evaluate and prepare for incorporating microreactor technology as the future energy source for district utility systems.

Challenges for District Energy Systems

The perennial issues faced by the nuclear industry are the same ones that must be addressed when evaluating a district energy system's incorporation of microreactor technology.

Safety and Fuel Storage

Though all the advanced reactor technologies under development are designed as passively safe systems — meaning they avoid the risk of potential failures faced by traditional light-water reactors — on-site storage of spent fuel is an operational issue that must be addressed. With many campuses located in or near highly populated areas, long-term fuel storage on-site would be undesirable. Containerized microreactors could provide a workable solution for this challenge, however, with wholesale replacement of the entire reactor module when refueling becomes necessary (typically expected to be eight years or longer).

Security

The NRC has published proposed alternate rules for physical security requirements of advanced reactors to include topics such as elimination of on-site dedicated armed responders, reliance on local law enforcement or other armed responders, engineered systems or human actions designed to delay incursions by intruders, and options for locating the secondary alarm station off-site. These protocols must be evaluated when siting a microreactor.

Fuel Availability

Fuel availability is another risk factor. Most advanced reactors are designed to use high-assay low-enriched uranium (HALEU). These HALEU fuels are enriched to between 5% and 20% U-235, compared to the low-enriched uranium used by light-water reactors. This energy-dense fuel provides for a smaller core, and thus, a more compact reactor design. Development of domestic HALEU fuel enrichment facilities is underway in the U.S. market, but it will be several more years before HALEU is commercially available. Protypes are now being tested by the Department of Energy (DOE), and results have been promising, but HALEU fuel has been available only in very limited quantities and has yet to enter domestic commercial production. DOE expects larger quantities of HALEU fuels will not be available until 2030 at the earliest. One company is preparing for prototype testing at Idaho National Laboratory in 2025. Some microreactors are being designed to use standard low-enriched uranium (LEU), used in conventional commercial reactors today, as an interim fuel solution.

Operations and Maintenance and Control

Extensive training on new technology would be required for district energy personnel. General operations and integration with campus utilities would be one primary issue, while procedures to operate and control the reactor introduces a completely new technology that would be unfamiliar to many. The standardized design and passive safety features inherent with microreactors, however, promise a far lower level of operational complexity compared with commercial reactors.

Cost

While some tax credits and other incentives are available under the U.S. Inflation Reduction Act (IRA), institutions willing to serve as early adopters are likely to bear a large cost burden to advance this technology. The price of constructing these technologies is still a moving target for first-of-a-kind installations.

Licensing and Permitting

The cost and schedule associated with the current NRC reactor licensing process is untenable for a campus energy application. There are two primary NRC licensing pathways for nuclear power facilities, and both take approximately four years to complete just to receive an approved permit for construction. These processes have been in place for decades and are tailored for licensing of large commercial light-water nuclear reactors. Universities may have an expedited licensure option, however. Applying to the NRC for a license for a nonpower, or research, reactor could help avoid the extended and costly review required under the current licensure pathways. However, research reactor licensing limits usage to a defined steam output.

University Test Case

A prominent Eastern U.S. research university is currently conducting a due diligence review aimed at eliminating fossil fuel use in its district energy system and incorporating a nuclear microreactor to produce thermal energy for the campus. The decarbonization plan sets a goal to achieve net zero emissions by 2026 and to eliminate all direct carbon emissions from its campus by 2050. As part of its near-term strategy prior to installing a microreactor, the university aims to offset its emissions by installing large-scale solar and wind energy facilities in an off-campus location while also reducing on-campus energy usage.

The goal of this project is to pursue a licensing and development process that would prove the viability of utilizing advanced nuclear technology for district energy applications. Burns & McDonnell has developed a study exploring options for integrating microreactor technology as a long-term district energy resource for the university's entire campus. The market for nuclear technology is converging and the overall purpose of the study was to provide the needed support for taking informed and incremental steps toward a zero-carbon future.

The primary goals of the evaluation included:

- Maintaining highly resilient utilities.
- Adopting a low-carbon energy source with the goal of emitting no carbon from any district energy source.
- Maintaining high-quality power and thermal energy sources.

Picking the Technology Pathway

Upon completion of a rigorous screening process, the Burns & McDonnell review team short-listed three technologies under development, ultimately recommending a system incorporating heat pipe reactor technology. This nominal 15-megawatt-thermal (MWt) reactor would be configured for an operational limit of 10 MWt for licensure as a research reactor initially. The heat produced off the back end of the reactor would be used to generate steam for distribution throughout campus.

The selected reactor is described by its manufacturer as a nuclear battery designed for safe and reliable power and heat production. The heat pipe technology has been widely tested and proven effective for passive cooling. It is designed to deliver a long core life, high-speed load-following capability, ease of installation, and elimination of the need to store spent fuel on-site, while providing flexibility for both heat and power applications, while requiring a limited number of on-site operating staff.

The licensing application for the unit would initially seek approval under the research reactor pathway, limiting initial use to steam production only. This operations profile would mean that only enough fuel loading for 10 MWt of output would be required. On-site refueling of the reactor would not be required as the entire containerized unit would be removed and transported away while a new unit is installed.

The selected microreactor would be capable of utilizing LEU fuel — the same fuel used in conventional utility light-water reactors — in the interim until HALEU is approved by NRC and available for commercial use.

The plan establishes an eight-year development cycle for a single microreactor unit as a means to control initial costs and position the project for potential qualification for federal tax incentives under IRA as well as other benefits that could be forthcoming from Congress.

Final Hurdles

Matching the most applicable nuclear microreactor technology with the unique needs of a particular district energy system requires an extensive and rigorous evaluation. A methodology developed by the Electric Power Research Institute (EPRI) can provide a road map for district energy utilities to carefully work through all considerations of matching an appropriate nuclear technology with specific system needs.

The EPRI framework helps address the two most pressing challenges facing the widespread adoption of advanced nuclear technology: cost, and public perception of safety. EPRI's Advanced Nuclear Technology program aims to accelerate the deployment of nuclear power around the world through dozens of research efforts focused on mitigating operational risks and uncertainties.

Cost is always a challenge for district utilities, even when conventional fuels and systems are being considered. The barriers of competing priorities on a campus within annual budgeting cycles often pushes district energy infrastructure upgrades and replacements to the bottom of the list. It is common to take years for utility upgrades to gain approval.

When nuclear energy is added to the equation, the public education component becomes an added layer of complexity. It will take a consistent effort over time to help shine light on the factors that make new advanced reactor technologies inherently safe. The always-on, safe delivery of high-quality energy must be considered as a key element for the long-term goal to decarbonize district energy systems.

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