U.S. DEPARTMENT of ENERGY

DRAFT REPORT

Microgrids R&D Strategic Plan

Topic 7 – Small Nuclear Reactors in Future Microgrids

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Disclaimer

Authors

The authors of this report are:

Timothy McJunkin, Bikash Poudel, Aaron Epiney, Ning Kang, Kurt Myers, Abdalla Abou-Jaoude (INL – Idaho National Laboratory)

Rachid Darbali-Zamora, Andrea Mammoli, Michael E. Ropp, Kenneth Armijo, Lauren Drakopulos, Gretchen Gano, Liliana Bastian, Margarete Wilson, and Laura Price (SNL – Sandia National Laboratory)

W. Neal Mann (ANL – Argonne National Laboratory)

Rob Hovsapian (SRNL – Savannah River National Laboratory)

J Michael Grappone (LLNL – Lawrence Livermore National Laboratory)

List of Acronyms

AC	Alternating Current
AI	Artificial Intelligence
ARIES	Advanced Research on Integrated Energy Systems
ASME	American Society of Mechanical Engineers
BESS	Battery Energy Storage System
BPVC	Boiler & Pressure Vessel Code
CESER	Cybersecurity Energy Security and Emergency Response
CHIL	Control Hardware-in-the-Loop
CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
DERMS	Distributed Energy Resources Management System
DETAIL	Dynamic Energy Transport and Innovation Laboratory
DOE	U.S. Department of Energy
DOME	Demonstration of Microreactor Experiments
EMT	Electromagnetic Transient
FOAK	First-of-a-Kind
FORCE	Framework for Optimization of Resources and Economics Ecosystem
HIL	Hardware-in-the-Loop
HPC	High Performance Computing
HTSE	High-temperature steam electrolysis
IBR	Inverter-Based Resources
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory

LEL	Large Electric Loads
LLNL	Lawrence Livermore National Laboratory
LWR	Light Water Reactor
MIB	Microgrid-in-a-Box
ML	Machine Learning
MACS	Microreactor Automatic Control System
MAGNET	Microreactor AGile Non-Nuclear Experimental Test Bed
MARVEL	Microreactor Applications Research Validation and Evaluation
MDT	Microgrid Design Toolkit
NE	(U.S. DOE) Office of Nuclear Energy
NNSA	National Nuclear Security Administration
NOAK	Nth-of-a-Kind
NREL	National Renewable Energy Laboratory
NRC	U.S. Nuclear Regulatory Commission
NRIC	National Reactor Innovation Centre
OE	(U.S. DOE) Office of Electricity
OPAL-RT	Open Platform for Advanced Simulation - Real Time
PHIL	Power Hardware-in-the-Loop
PERL	Power and Energy Real-Time Laboratory
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
RD&D	Research, Development, and Deployment
RTDS	Real-Time Digital Simulator
SHARCC	Sandia’s Holistic Advanced Reactor Capabilities Center
SMR	Small Modular Reactor

SNL	Sandia National Laboratory
SNRMC	Small Nuclear Reactor Microgrid Consortium
SR	Small (Nuclear) Reactor
SRNL	Savannah River National Laboratory
T&D	Transmission and Distribution
TA	Technical Assistance
TEDS	Thermal Energy Delivery System
TREAT	Transient Reactor Test Facility
TRISO	Tri-structural ISOtropic

Executive Summary

Mission-critical commercial and military applications have extremely high uptime requirements and tight deployment space constraints. Advanced small nuclear reactors[1], packaged as compact units and deployed in microgrids, present a tantalizing option to meet these constraints and advance many of our nation's priorities.

The need to accelerate deployment of nuclear powered microgrids include:

- Transporting fuel and water resulted in over half the American casualties in the Iraq and Afghanistan wars provides one driving imperative to localize nuclear energy in military microgrid applications that include the abundance of energy to desalinize and purify water sources.
- Removing barriers for large load application developers needing to "bring your own power" to ensure the nations AI and industrial dominance.
- Relieving pressure on the need to build out expensive and time-consuming electricity and gas infrastructure to power our artificial intelligence and industrial dominance.
- Creating energy dominance solutions for mining of energy industry resources by enabling portable microreactors, which have the capacity to support remote extractive sites.

Implementing first-of-a-kind demonstrations of such emerging nuclear capabilities comes with new challenges requiring a multi-office approach from the U.S. Department of Energy (DOE) to bridge advanced nuclear reactor technology to emerging nuclear energy entrepreneurs and aspiring nuclear powered application developers. DOE Office of Electricity (OE) and national laboratory complex provide the nation with the brain trust needed to build out the facilities and develop the capabilities American industry and commerce need from nuclear-powered microgrids. DOE-OE's Microgrid Program leverages its long-standing role to advance new technology through partnerships with other DOE offices, government agencies, and industry. The Microgrid Program's Nuclear Powered Microgrid initiative (NPM) is designed to accelerate private sector-led innovation to advance grid reliability, resilience, security, and affordability through collaboration with the Office of Nuclear Energy's Microreactor Program. It does so by providing unique platforms and capabilities throughout the DOE laboratory complex to accelerate demonstration and deployment that advance the robustness of for first-of-a-kind nuclear powered microgrids. Because the historical delays and cost overruns of large nuclear power plants will not suffice, the initiative intends to collaborate with DOE's Office of Nuclear Energy (DOE-NE) Light Water Reactor Sustainability

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[1] Small nuclear reactors encompass both advanced small modular reactors and microreactors typically sized as 100 MW and under that can be readily used for microgrids applications

Program's Capacity Expansion Pillar to establish regulatory frameworks that provide certainty to microgrid application developers. Defeating the regulatory and technological barriers for these innovations is an imperative. Finally, it intends to cultivate industry-driven technical standards and best practices for enhanced grid reliability, resilience, security, and affordability. The programmatic plan illustrates the NPM's steadfast approach to rapidly harness nuclear-powered microgrids.

Nuclear power has unique attributes that microgrids can take advantage of. Nuclear-powered microgrids will potentially run for up to 10 years without refueling, operate at a capacity factor of 95% or more, require only 1 acre to serve a load of 20 megawatts, and lower the cost of electricity by more than 50% in remote communities, military or industrial applications that use diesel generators.[2] Modularity and transportability of small reactors make them ideal for remote site applications that are challenged by lack of electricity transmission or potential disruption of fuel supply. Factory production will drive down costs. Advanced small reactors are safe by design[3,4], thereby mitigating the risks traditionally associated with nuclear energy and improving the already exceptional safety record of the U.S. nuclear power industry. Unlocking the full potential of nuclear-powered microgrids requires a concerted research effort to tackle key gaps and challenges:

- Implement control and protection strategies in new nuclear powered microgrid management systems to seamlessly integrate the interactions between thermal and electrical storage with the unique characteristics of small reactors.
- Finalize new microgrids standards, codes, and guidance that specifically address the unique characteristics of small reactors for small reactors and microgrid developers.
- Demonstrate nuclear powered microgrids to foster public and stakeholder understanding and engagement to help tackle regulatory challenges and social acceptance.
- Develop a testing platform to rapidly move nuclear powered microgrid development from conceptual and preliminary design to incremental testing of real-world components and control systems through to deployment.

To address these gaps and challenges, the NPM initiative has been established as an R&D area within the Microgrid Program. This includes dedicated resources and expertise designed to reduce development risk and accelerate the commercial adoption of nuclear powered microgrids. This is accomplished through the development of a

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[2] Cost comparisons with other energy sources are based on Nichol and Desai's 2019 report, "Cost Competitiveness of Micro-Reactors for Remote Markets," published by the Nuclear Energy Institute

[3] New and Advanced Nuclear Reactors in the United States National Academies of Sciences, Engineering, and Medicine. 2023. https://doi.org/10.17226/26630. – Chapter 2 section "Safety Characteristics"

[4] Utilize passive safety systems, integrated modular structures with reduced piping, coolants with high boiling points, and advanced accident-tolerant fuels that withstand high temperatures and have undergone rigorous testing to ensure nuclear fuel is contained under any accident scenario.

standard nuclear microgrid design and pre-deployment testing framework to validate system integration while avoiding the risks and costs associated with direct experimentation on one-of-a-kind equipment. The framework includes technoeconomic feasibility analysis, energy management and control system design to coordinate nuclear, energy storage and other grid assets, system transient modeling and control validation, and power and control component testing.

Small Modular Reactor is one document in a series of nine strategy papers that dive deeper into specific Microgrid R&D program focus areas:

1. Program vision, objectives, and R&D targets in 5 years
2. T&D co-simulation of microgrid impacts and benefits
3. Building blocks for microgrids
4. Microgrids as a building block for the future grid
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. **Small Nuclear Reactors in Future Microgrids**
8. Artificial Intelligence and Machine Learning for Microgrid Applications
9. Enabling regulatory and business models for broad microgrid deployment

Grid and microgrid integration of advanced nuclear reactors has not been a focus of reactor developers or the DOE-NE. This present an ideal opportunity for partnership with the Office of Electricity to support a new paradigm of locally sourced power, including nuclear power, thermal energy storage, and inverter-based-resources (IBR), i.e., battery storage and locationally opportunistic variable generation, will create new challenges and opportunities for managing power generation, storage, utilization, quality, security, and resilience at the edges of transmission and distribution for electricity utilities. The DOE OE Microgrid and Energy Storage Programs, combined with the NE programs, Cybersecurity Energy Security and Emergency Response (CESER), and others, are positioned to address these emerging energy challenges through a collaboration of DOE national laboratories.

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1 Introduction

1.1 Nuclear Power for U.S. Energy Dominance

After years of stagnant demand, many regions of the North American power system now face rapid load growth driven by data centers (Shebabi et al. 2024), industrial expansion, and the retirement of coal and aging natural gas plants. Utilities and power producers need new solutions to maintain resource adequacy and reliability (NERC 2025), but deployment of intermittent generation, grid-scale energy storage, and transmission is not keeping pace. Near-term options include siting new generation closer to load or co-locating flexible loads near existing plants. Natural gas generation could be sited near new data centers, and companies could, in turn, locate new data centers near transmission hubs or existing, restarted, or new nuclear plants (Mark and Sullivan 2024). Recent examples include Microsoft and Constellation's effort to restart Three Mile Island Unit 1 to meet rising demand (World Nuclear News 2024); and Amazon Web Services' PPA with the Susquehanna nuclear station, which increases competition for existing nuclear output (Talen Energy 2025). The nuclear industry's renewed prominence is further reflected in life-extension plans for the current fleet, Holtec's restart of Palisades (Walton 2025), Terrapower's Natrium project in Wyoming (TerraPower 2024), and growing vendor interest in test facilities at INL and other national labs.

The resurgence of companies seeking to build advanced small reactors (SR), which includes both microreactors and small modular reactors (IAEA 2024); DOE's investment in small reactors, like MARVEL (Spangler 2025); and nuclear energy testing infrastructure like DOME (NRIC 2025) are indicators that the long-awaited nuclear renaissance is here. To usher in this long-awaited nuclear renaissance, the deployability, affordability, security, and resilience of nuclear-powered microgrids must be demonstrated to accelerate the adoption of nuclear energy as a major contributor to the United States' goals for energy abundance and affordability.

1.2 Nuclear Power and Microgrids

Grid and microgrid integration represents a major opportunity for expanded DOE leadership, as it has not traditionally been a central focus for novel reactor vendors or DOE's Office of Nuclear Energy. Industry interest is strong: INL, on behalf of the DOE OE Microgrid Program, has received letters of support from eight microreactor developers, two application developers, and one electric generation utility as of August 2025, highlighting the need for DOE engagement in application integration. This collaboration supports new locally sourced power that integrates nuclear generation, thermal energy storage, and locationally opportunistic generation resources. This shift in focus creates substantial opportunities to improve power quality, security, resilience, and operational flexibility. Multiple configurations for energy generation, conversion, storage, and delivery can be developed using standardized building blocks. Digital engineering further accelerates and reduces deployment costs through standardized, high-fidelity models validated across diverse experimental facilities.

The SR-based microgrid research will heavily leverage the other areas of research from the Microgrid program:

- *Transmission and Distribution (T&D) Co-simulation of Microgrid Impacts and Benefits*.
- *Building Blocks for Microgrids*.
- *Microgrids as a Building Block for Future Grids*.
- *Advanced Microgrid Control and Protection*.
- *Integrated Models and Tools for Microgrid Planning and Designs with Operations*.
- *Artificial Intelligence and Machine Learning for Microgrid Applications*.
- *Enabling Regulatory and Business Models for Broad Microgrid Deployment*.

This strategic plan outlines a coordinated R&D pathway to accelerate SR deployment, strengthen cross-lab integration of SRs as electrical and thermal assets, and position them as standardized, interoperable components of future microgrid platforms. Their modest footprint, long-life fuel, high availability, and inherent safety features (NASEM, 2023) make small reactors well suited for diverse applications. Modular, factory-produced SR designs further position them for deployment on traditional grids and in remote sites with limited transmission access or vulnerable fuel supplies. These attributes enable SRs to help close emerging gaps in resource adequacy and support critical infrastructure under stress from extreme weather or malicious attacks. Ultimately, this work will enable reliable, secure, and affordable energy for the nation and help unlock a new era of American energy dominance.

2 Vision of the Future

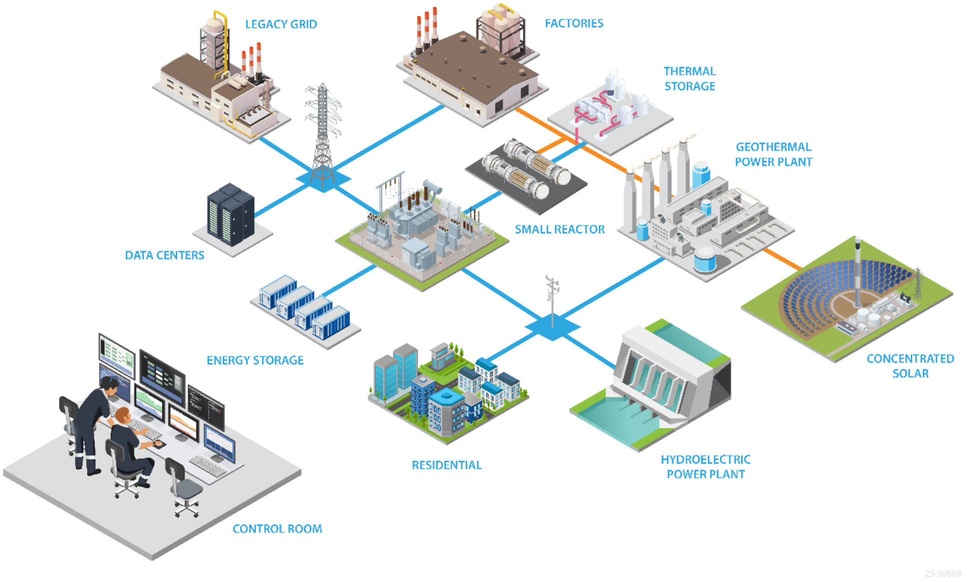

Figure 1. Vision of small reactor based microgrids that support key energy growth areas: data centers that require high-quality electricity and industrial loads that require both heat and electricity.

The vision of this strategy, illustrated in Figure 1, fosters the acceleration of nuclear energy adoption in numerous applications that require stable and long-term energy assets by creating the foundational testbeds, platforms, resources, and methods to support private industry in accelerating the deployment of nuclear energy for key emerging energy applications, including data centers, industrial processes, and military installations in both remote and urban settings.

The DOE-OE Microgrid program sets the following goals to be successful in nuclear microgrid research:

- Formation of the Small Nuclear Reactor Microgrid Consortium (SNRMC) to create an industry stakeholder-driven community to define and execute needed R&D at the national laboratories and academia.
- Near-term demonstration of Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor power delivery to microgrid in FY 2028.
- New, localized power sources to address the significant demand growth in North America's power system due to data center growth and manufacturing onshoring.

- Address challenges associated with new paradigms of microgrid technologies, including SR, thermal storage, and other locally available energy sources using standardized energy management systems
- Digital engineering and standardized models will be applied to reduce microgrid design, demonstration, and deployment costs
- Continued alignment of the research programs in DOE-OE and DOE-NE in conjunction with industry needs.
- Establish simulation, controller-in-the-loop, and hardware-in-the-loop testing as standard practices to accelerate deployment and improve decision confidence before physical demonstration.

3 Research and Development

3.1 Managing the Small Reactor Microgrid Application

Successful deployment of SR-based microgrids requires tight coordination of traditional electricity and combined heat and power (CHP) control systems with advanced control strategies capable of coordinating nuclear, thermal, and locally available energy sources. Figure 2 illustrates the main blocks of the combined SR-based microgrid system, the low-level control systems, and the overarching application management system that operates the application(s) of the microgrid. The integration of SRs into microgrids introduces a new type of highly reliable, continuous electricity and heat generation. Advanced control strategies that integrate nuclear, thermal, and local energy sources will be key to maximizing the impact of SRs. These control systems must ensure operational flexibility, safety, and regulatory compliance while maximizing the microgrid’s resilience and performance. SRs demand highly reliable, safety-critical controls, especially when operating within microgrids that include variable generation and storage. In such settings, control systems must support autonomous operation, islanding and resynchronization, and dynamic load balancing across both dispatchable and intermittent resources.

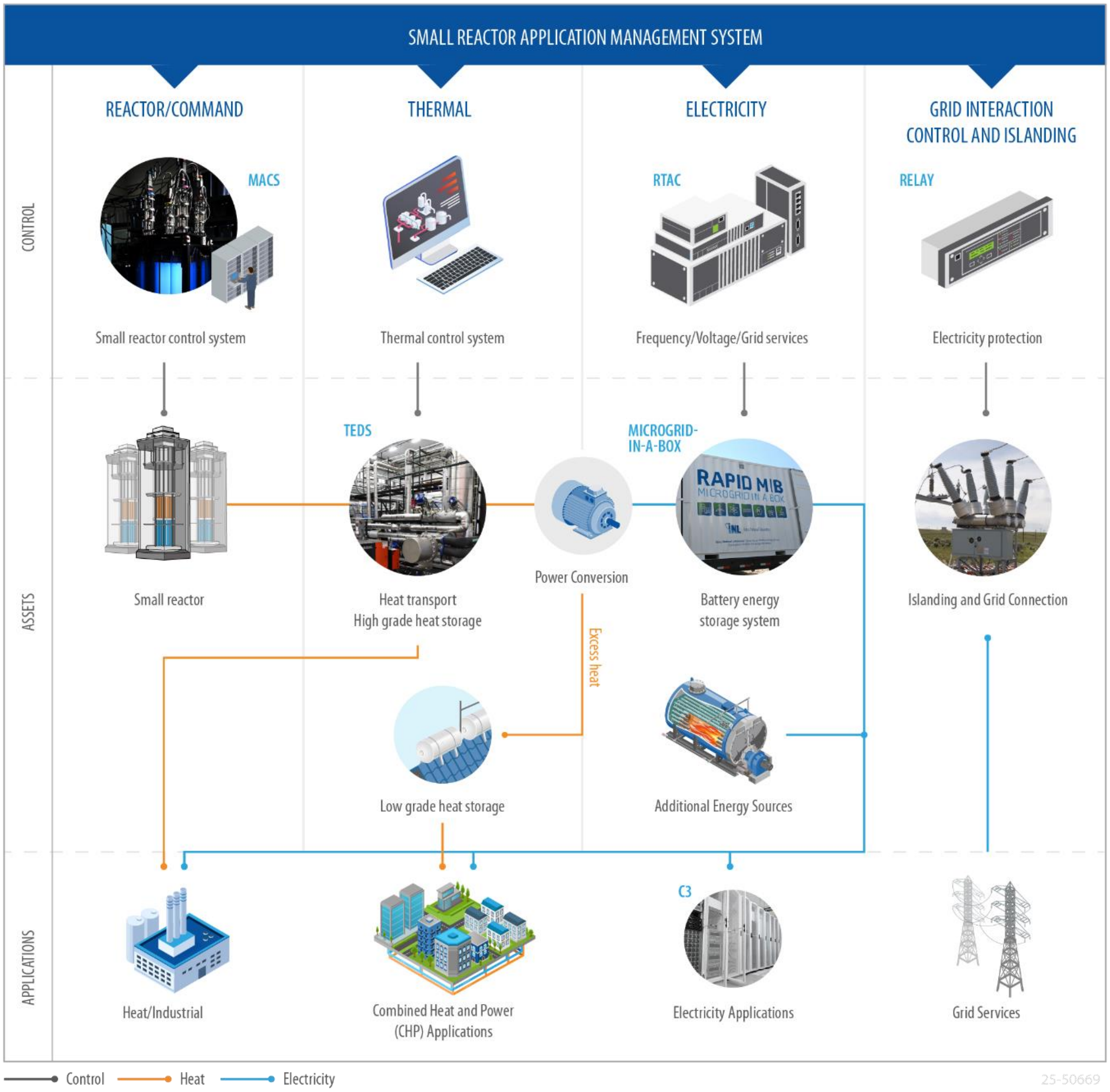

Figure 2. The SR application management system must both leverage existing electric and CHP microgrid systems while also managing new high-grade heat availability.

3.1.1 Advanced reactor flexibility and black start

The loads on an electric power system change continuously in real-time. Thus, the power ramping capabilities of power sources are important in microgrids, where load variability[5]. Large nuclear reactors have limited load following capabilities and thus have been traditionally operated in a “baseload” mode, in which their output power is relatively

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[5] SAND2025-00453, “An exploration of how the geographic distribution of power sources impacts power system resilience”, https://www.osti.gov/servlets/purl/2516820.

constant, leaving other sources to handle the variability in the load. Their minimal load following capabilities also limit the total amount of traditional nuclear power that a power grid can accommodate. Some SR designs have significantly better dispatch agility (Zhang and Jiang, 2024) and so require less equipment to handle load variability, and the potential to support black starts. Overall SR will have decreased complexity and lower overall cost.

Operating an SR within its ramping capabilities in a microgrid will, nonetheless, require SRs to integrate with other technologies such as fast-acting energy storage and load control. The controls for an SR-based microgrid must coordinate the responses of all generation technologies through tools that provide to coordinate SR plant output with the level of energy available in the energy storage systems.

3.2 Thermal Systems Integration

SRs provide both electricity and high-quality heat. Microgrids can utilize both unused primary heat and waste heat to improve the overall economics of the system. Effective integration of SRs into microgrids requires co-optimization of both the power and thermal loops, which can support not only electrical load but also additional applications, such as district heating, absorption cooling, desalination, chemical and synthetic fuel production and industrial process heat. Electrical storage is already used in microgrids to decouple electrical loads from power generation when needed. Thermal storage adds additional layers of flexibility, which can enhance the operation of an SR-based microgrid. Thermal storage can be used both for electric power and/or for the direct use of heat.

3.2.1 Small Reactor Heat Output Characteristics

In a combined electrical and thermal microgrid system, both electric load and thermal load must be balanced. When comparing electricity, heat, and chemical energy within integrated SR-based systems, exergy (defined as available energy) is the preferred metric because it allows all energy forms to be evaluated on a common basis (IAEA 2017, Robinett and Wilson 2011). Exergy represents the maximum useful work obtainable from a given energy source; for thermal energy it depends on the temperature difference with the environment, while electrical energy has an exergy value essentially equal to its energy content. Although systems can also be optimized for cost, resilience, or reliability, integrating SRs into microgrids introduces design-specific complexities that can create tradeoffs among these objectives. These tradeoffs (and their diminishing returns) remain insufficiently understood and will vary by application. Evaluating them requires tools such as Framework for Optimization of Resources and Economics Ecosystem (FORCE) tools, Xendee or the Microgrid Design Toolkit (MDT), and their use should be standardized to ensure consistent assessments and accumulated expertise.

3.2.2 Thermal Storage

Thermal storage enhances SR-based microgrid operations by buffering between the reactor’s limited output variability and loads that cannot be easily deferred or modulated. Selecting a storage configuration can be complex: thermal storage can support both electricity generation and direct use of heat applications. Operators additionally have the option to store energy as heat before conversion (into electricity) or as electricity after conversion. These choices cascade down the temperature scale, allowing lower-quality heat to serve additional uses within the microgrid.

3.3 Microgrid Design Considerations of Small Reactor Technologies

This section provides a high-level summary of the design and performance characteristics most important to microgrid design and operation. The capabilities of SRs, such as flexibility in adjusting output, are crucial for the operation of a microgrid. SRs are next-generation advanced nuclear reactor technologies that will be significantly different from the existing reactor technologies developed for the U.S. Navy and the current fleet of light-water reactors (LWRs) that serve as a major power source nationwide. Generation I and II reactors have established themselves as significant contributors to the US power system, demonstrating low production costs (less than 2 cents/kWh) and superior capacity factors (over 90%), accounting for 18.2% of generation in 2024 (IAEA 2025). The classes of reactors and their basic characteristics are determined by the primary cooling medium that transports heat from the core. These types include advanced water-cooled, high-temperature gas-cooled, liquid metal-cooled, heat pipe and molten salt reactors (IAEA 2025b). Highlights of each type relevant to prospective microgrid applications are summarized here (details can be found in Poudel et al. 2023):

Table 1. Advanced reactors technologies by coolant type.

Technology	Coolant and Temperature Range (°C)	Key Advantages	Key Challenges	Operational Characteristics	Potential Applications
Water-Cooled SRs	Water 250 – 300 °C	Extensive industry experience, reduced containment size	Limited to low-temperature applications	Natural circulation, integral designs	Low-temperature industrial processes, marine applications
Liquid-Metal Cooled SRs	Na, Pb, K 400 – 600 °C	High heat-removal capacity, long operational period	Chemical reactivity, corrosion issues	Fast-neutron spectrum, high thermal efficiency	Remote microgrids, long-duration operations
Heat-Pipe Liquid-Metal SRs	Na, K, NaK 760 – 880 °C	Passive circulation, high efficiency, low maintenance	Material compatibility at high temperatures	Simple design, high-temperature operation	Process heat applications, small modular systems
High-Temperature Gas SRs	Helium, CO_2 750 – 950 °C	High-temperature output, inherent safety features	More frequent refueling due to high burnup rates	Low pressure, TRISO particle fuel	Industrial heat applications, hydrogen production
Molten-Salt Cooled SRs	Molten salts (Cl, F) 650 – 800 °C	High efficiency, low-pressure operation	Corrosion control, larger size, higher capital costs	Liquid fuel handling, high thermal efficiency	Electricity generation, high-grade process heat

The choice and characteristics of nuclear fuels directly influence the performance, safety, economic viability, and sustainability of nuclear technologies, making them particularly relevant for microgrid implementations. Notably, fuel developments like those in TRISO have significantly addressed safety and proliferation concerns in microgrid deployments (Office of Nuclear Energy 2019).

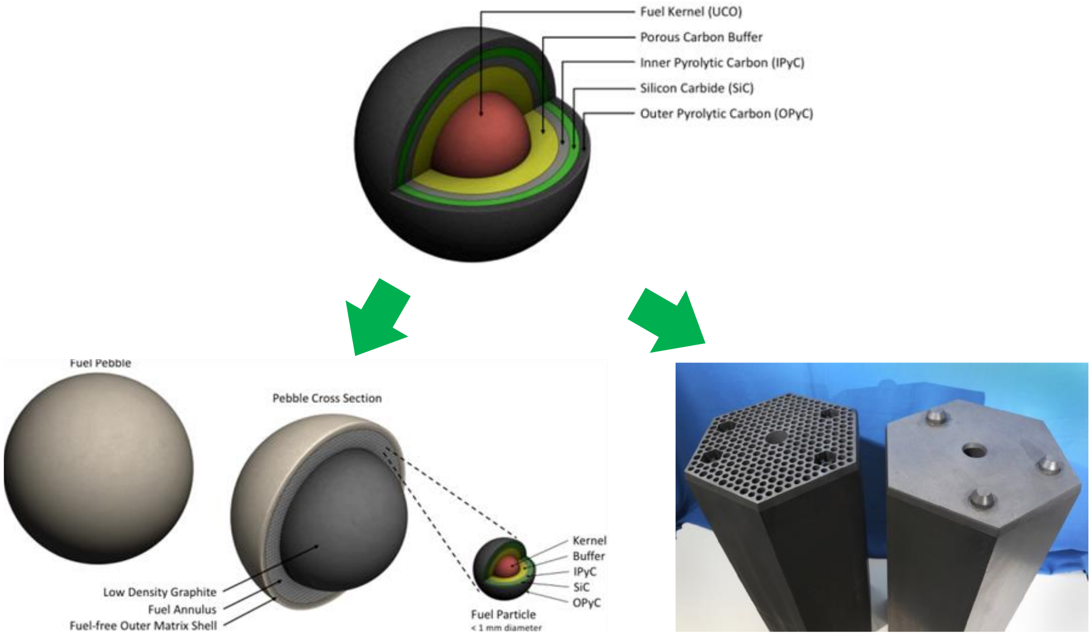


Figure 3. TRISO fuel structure used in spherical fuel pebbles and prismatic graphite blocks.

3.4 Power conversion Systems

The characteristics of an SR's power-conversion system are important to its operation within a microgrid. The heat engine converts heat produced in the reactor through fission reaction into mechanical work. The heat engines vary depending on the type of fluid involved and the thermodynamic processes. The primary classes power conversion include Rankine, Brayton, combined cycle, and Stirling engines.

Table 2. Typical power conversion types, key characteristics, challenges and prospective reactor uses

Power Conversion System	Working Fluid	Temperature Range (°C)	Key Advantages	Key Challenges	Typical Applications
Rankine Cycle	Water	200–600	Well-established, high efficiency with superheating	Limited to low-to-medium temperatures	Conventional nuclear power plants
Brayton Cycle	Helium, CO2, Air	500–1600	Continuous operation, high-temperature capability	Higher rotational speeds, large volumes	High-temperature and advanced reactor designs

Power Conversion System	Working Fluid	Temperature Range (°C)	Key Advantages	Key Challenges	Typical Applications
Combined Cycle	Gas (Brayton) + Steam (Rankine)	450-1600	High overall efficiency, utilizes waste heat	Complexity in design and operation	Advanced nuclear plants, hybrid systems
Stirling Cycle	Helium, Hydrogen	650-800	High thermal efficiency, fewer moving parts	Limited to specific applications	Small mobile SR technologies, space applications

The mechanical power produced by heat engines is used to drive electric generators. Although not all details of every SR design is publicly available, it is expected that electricity will be produced by a variety of synchronous and non-synchronous generators. This variety of technologies necessitates planning for integrating inverters into the AC grid alongside traditional synchronous machines. The implications for black starts and determining which assets need to function as the grid-forming engine also need to be addressed, which is a recognized gap in the knowledge of SR vendor design details.

4 Key Gaps Outside of Technical R&D

4.1 Codes and Standards Gaps for SR Microgrids

SRs occupy a unique space between traditional utility-scale nuclear plants and decentralized energy systems. When integrated into microgrids, especially those containing intermittent generation, energy storage, and flexible loads, SRs must operate in both islanded and grid-connected modes, interact with inverter-based resources, and participate in real-time control and protection schemes. However, current codes and standards often treat nuclear and other assets as separate classes, resulting in inconsistencies and integration friction. Therefore, the deployment of SRs in microgrids is likely to face several critical codes and standards gaps.

- Interconnection standards:

  Any SR connected to a distribution system would be subject to the requirements of IEEE 1547, but this standard lacks explicit consideration of any unique needs or characteristics of the interconnection of an SR-based power plant, inside or outside a microgrid.

  NRC guidelines focus on centralized grid connection, not islanded microgrid operation. SRs connected at the transmission level would be covered by all the applicable NERC standards, such as NERC NUC-001, but these were written without explicit consideration of the unique properties of SRs. IEEE 2800 would not apply in this case unless an SR power plant were interfaced to the grid via inverters.

- Interoperability standards:

  Existing standards like IEEE 1547.3, which covers device interoperability and cybersecurity, and IEEE 2030-2011, which introduces the Smart Grid Interoperability Reference Model (SGIRM), would interact with NERC CIP and other security requirements for nuclear power plants.

- Safety standards:

  In the United States, the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency manage most portions of the Code of Federal Regulations (CFR) pertaining to nuclear safety. It is assumed that these will apply equally to SRs.

  However, if an SR were to be used in a microgrid, it would necessarily be located near human-occupied spaces. A new set of safety standards and requirements will need to be developed to address this case.

- Design standards:

  No industry-wide design standards currently exist for SR-based power plants.

  Individual SR manufacturers are developing plant designs around their specific SR designs. Several manufacturers, such as NuScale and Rolls Royce, have announced standardized plant designs.

- Local Energy Resource Standards

  NFPA 110, UL 1741, and American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code (BPVC) also do not directly address SRs or their interaction with inverter-based localized energy sources, thermal systems, or hybrid control structures.

This lack of alignment creates regulatory uncertainty that hinders technical advances, innovation, and deployment, and must be addressed through additional standards work.

4.2 Co-siting with large loads

SRs are increasingly being considered for co-siting with large thermal and electrical loads, such as data centers (Shaikh 2025) and industrial processes (Vanatta 2023), where careful selection of heat-extraction points is essential. Thermal integration (Section 3.2) can also help align reactor output with variable industrial demand across both heat and electricity.

Islanded microgrids for critical mineral mining or defense installations face additional challenges, including limited access, high resilience requirements, and logistical constraints. These conditions necessitate right-sized SRs with integrated controls, storage, and fault tolerance. Siting must consider deployment logistics, load profiles, and required system autonomy to ensure mission-critical performance.

However, there has been little research into siting and placement frameworks for co-siting nuclear technologies with other resources in microgrids. This includes considerations for piping and instrumentation designs as well as electrical designs.

4.3 Public Awareness and Acceptance of SR centered microgrids

Public awareness of SRs remains low, highlighting the need for public education. While familiarity with SRs is associated with positive attributes like reliability and safety (Bisconti 2025), acceptance will depend on how communities weigh local energy benefits against perceived nuclear risks. Economic and regulatory constraints further shape social barriers, highlighting the importance of targeted engagement with influential stakeholders across sectors (Mignacca et al. 2020). Early-stage SR development offers an opportunity to address social license proactively, particularly as SRs intersect with microgrid deployment. Regional differences in social, environmental, and technological conditions will strongly influence how communities view SR–based microgrid projects, the types of social barriers that emerge, and the engagement strategies most likely to be effective.

Stakeholder needs vary by region, which makes early identification of the relevant actors at each development stage essential. Support from state decision-makers and regulatory bodies is particularly critical (Jeong 2024) as financial and regulatory frameworks for SR deployment take shape. Building social license requires transparent communication and engagement strategies that incorporate stakeholder needs into decision-making. Integrating these requirements at key SR–microgrid decision points will help guide socio-technical development and strengthen the capacity to anticipate and overcome implementation barriers.

4.4 Microgrid-Specific R&D Needs for Small Reactor Deployment

The following are examples of microgrid specific issues that need to be addressed as part of research and development:

- Transient and accident protection: Traditional reactors trip under major load or frequency/voltage disturbances, but microgrids may require safe ride-through capability. Achieving this demands coordinated controls and a clear understanding of reactor operating limits in normal and abnormal conditions.
- Safety, safeguards, and proliferation risk: Non-traditional microgrid use of nuclear power may elevate proliferation risks, requiring coordination with DOE-NE and National Nuclear Safety Administration (NNSA) programs responsible for nuclear safety and security.
- Automatic and integrated operations: Current reactors require specially trained operators, but many microgrid applications will depend on SRs operating autonomously under microgrid control. This significant regulatory barrier is amplified in the microgrid context.
- Area constraints: Area constraints are critical for microgrid deployment; in space-limited urban settings, compact SR designs with reduced emergency planning zones are preferable to enable integration without significant land or cost impacts.

5 Use Cases and Scenario Examples

5.1 Review of Applications and Design Criteria for SR Based Microgrids

SR technologies offer adaptable and efficient energy solutions suitable for a broad range of microgrid applications. Their compact size, modularity, transportability, scalability, long-lasting fuel, and inherent safety features, make them particularly relevant for addressing the unique energy challenges faced by various microgrid applications.

Table 3. Applications with strong small reactor relevance and feasibility

Microgrid Application	Relevance of Small Reactors
Remote and Island Communities and Mining Operations	Many remote and island communities depend on diesel generation, which creates fuel supply and cost challenges. SRs offer a reliable, potentially lower-cost alternative that can operate independently of the grid, significantly enhancing energy security and reliability in these regions. Mining operations may also be remote without sufficient transmission to support them from the bulk electric system.
Military Bases	SRs enhance energy security for mission-critical military infrastructure by providing reliable power in controlled environments that reduce physical and cybersecurity risks. When coupled with other energy sources, SR-based microgrids improve generation, resilience, and reliability for essential loads, including command systems, communications, and warfighter support facilities.
(Remote) Critical Infrastructure	Critical infrastructure facilities require uninterrupted power for essential functions, such as communications, control systems, and safety operations. SRs can replace diesel generators by providing continuous power capable of supporting extensive operational needs. Integrating SRs into microgrids enhances resilience during grid outages or extreme weather. Pairing SRs with energy storage enables rapid response to load fluctuations and emergency demands, helping to safeguard operations and revenue.
Commercial Applications (Data Centers)	Data centers are a strong commercial fit for SR-powered microgrids, given their need for reliable, stable, high-quality power. Typical data center sizes (40–60 MW) align well with the economic scale of many SRs. However, several technical challenges must still be addressed, including managing load variability; ensuring robust frequency and voltage control for large inverter-dominated loads; mitigating harmonics and power-factor issues; addressing sub-synchronous oscillations; and accounting for voltage-frequency–drive motor cooling systems.
Industrial Applications	Industries requiring both heat and power, such as manufacturing, petrochemicals, and food processing, are strong candidates for SR-based microgrids. SRs offer reliable electricity and high-grade process heat, but key technical challenges include the complexity of integrating simultaneous heat and power production and the high capital costs of the technology and associated infrastructure retrofits.

Microgrid Application	Relevance of Small Reactors
Rural Electric Cooperatives and Small Utilities	Small utilities and rural cooperatives stand to benefit from SR adoption, as they often face limited access to large-scale generation, dependence on wholesale power, aging infrastructure, and vulnerability to extreme weather disruptions. SRs offer a scalable, reliable option that can enhance energy security and reduce reliance on external suppliers. Key barriers include high upfront costs and limited local technical expertise available for operation and maintenance.
Space Stations of the Future	SRs' high fuel density and long operating life make them well suited for continuous, reliable power on space applications, such as lunar and Mars habitats, and future Earth orbiting space stations. SRs provide a dependable backbone for resilient operations, and designs can support both AC and DC outputs to meet diverse mission requirements.

5.2 Modeling SR for Microgrid Technoeconomic and Operations Analysis

Modeling SR-based microgrid for technoeconomic and operations evaluation requires an understanding of their unique operational and cost characteristics. Unlike traditional power generation technologies, SRs differ in terms of extended refueling cycles, process heat extraction, and additional operation constraints including baseload and power cycling limits. These factors must be accounted for in planning and dispatch decisions within a microgrid environment. To facilitate this, a generic SR modeling block has been developed and integrated into the Xendee platform with support from the DOE-OE Microgrid Program. Figure 4 contains example results from techno-economic optimization and hourly dispatch for two SR applications in the Xendee platform. The platform has been used to efficiently study the feasibility of an application with respect to the resources needed and costs considering the specific capabilities of an SR.

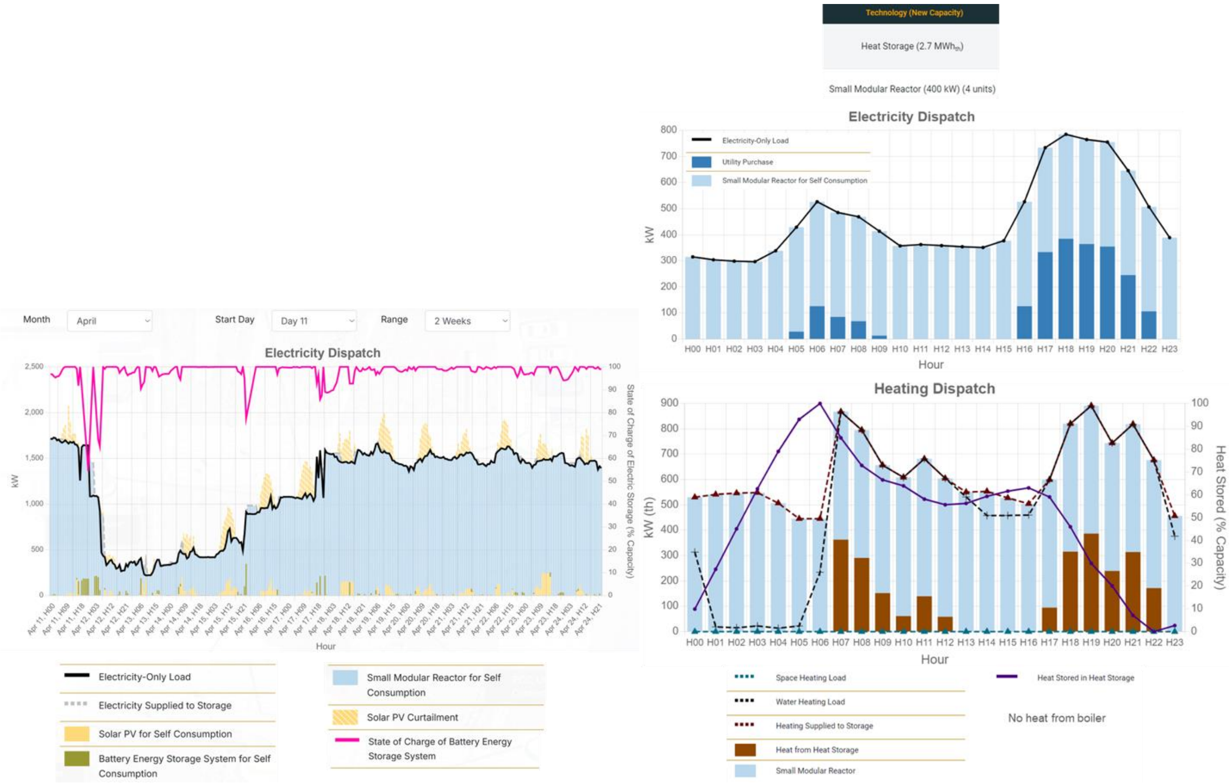
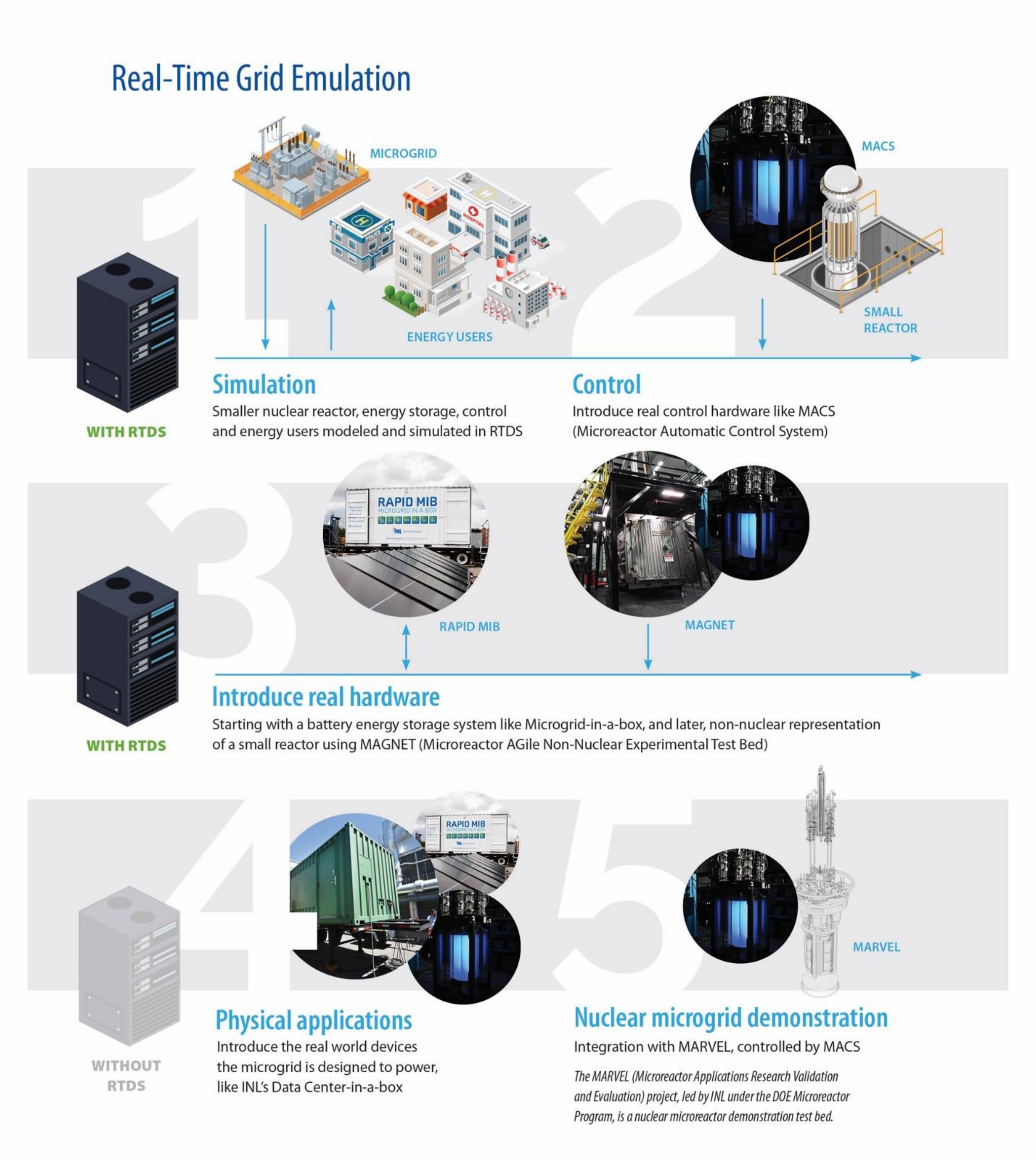


Figure 4. Two use case examples are illustrated. On the left a case explores the integration of an SR, BESS and PV for off-grid data center facility. And on the right, a use case explores the integration of an SR and thermal energy storage to support heat and electricity demand of a grid-connected microgrid (Poudel et al. 2023).

5.3 Real-Time Simulations of Small Reactors in Microgrids



Real-Time Grid Emulation

Simulation
Smaller nuclear reactor, energy storage, control and energy users modeled and simulated in RTDS

Control
Introduce real control hardware like MACS (Microreactor Automatic Control System)

Introduce real hardware
Starting with a battery energy storage system like Microgrid-in-a-box, and later, non-nuclear representation of a small reactor using MAGNET (Microreactor AGile Non-Nuclear Experimental Test Bed)

Physical applications
Introduce the real world devices the microgrid is designed to power, like INL's Data Center-in-a-box

Nuclear microgrid demonstration
Integration with MARVEL, controlled by MACS

The MARVEL (Microreactor Applications Research Validation and Evaluation) project, led by INL under the DOE Microreactor Program, is a nuclear microreactor demonstration test bed.

Figure 5. The approach used to incrementally build confidence in control system design and hardware integration towards demonstration and deployment.

The incremental approach illustrated in Figure 5 moves from a purely simulation environment towards the full demonstration. First by using of models of the MicroreactorAgile Non-Nuclear Experimental Test bed (MAGNET), the Microreactor Application Research Validation and Evaluation (MARVEL) microreactor and the Microgrid in a Box (MIB) (Hatch 2023) for use within the Real-Time Digital Simulator (RTDS) to study their behavior in microgrids. MAGNET and MIB models can integrate with other energy assets, like diesel and natural gas generators or variable resources when their location offers a strategic advantage, to support real-time analysis of operating conditions such as startup sequences and frequency regulation, providing insights into microgrid design. After validation, these models support a step-by-step transition from simulation to physical implementation. The step-by-step process of including real-world equipment begins with connecting controllers, followed by integration of battery storage (like MIB), a non-nuclear representation of a nuclear reactor (as in MAGNET), and electricity loads (such as a “data center in a box”), in preparation for the full demonstration of a nuclear-powered microgrid using a nuclear reactor with MARVEL. RTDS modeling facilitates the testing of physical components and control systems together with simulated components, particularly when certain elements are under development or too risky to test directly without prior operational experience.

Using models early in the development process allows microgrid developers to reduce deployment risks. Testing components with simulated models and physical hardware allows developers to evaluate system behavior, validate control strategies and identify integration challenges well before a physical reactor is built and tested. Studying the reactor’s performance in real time, alongside simulated and physical microgrid equipment, allows researchers to assess whether the system architecture, asset mix and control logic are appropriately configured for first- of-a-kind deployment.

RTDS and grid emulation enables modeling complex or in-development components such as small reactors described by neutronics, gas-Brayton heat transfer mechanisms and power conversion systems. This allows testing with high-fidelity representation of the system components without putting one-of-a-kind equipment at risk. Control systems integration including controller system hardware such as MACS, the MIB controller and the overarching microgrid management system or distribution energy management system. The functionalities provided by these controllers include temperature control and load-following capabilities. Testing of real-world equipment through integrating physical hardware into the RTDS test bed, as it becomes available, to gain operational experience. In this case, MAGNET/MARVEL will be paired with MIB via RTDS for real-time physical demonstration of grid scenarios, to be as prepared as possible for full demonstration using MARVEL.

The resulting platform will be customizable for any nuclear-microgrid system. The nuclear microgrid modeling framework is adaptable to support modeling a wide range of nuclear technologies and microgrid architectures. With minimal parametric changes, the RTDS-based model can simulate various small nuclear reactor designs, heat transfer systems and power conversion units. For example, point kinetics equations are used to model reactor dynamics, allowing quick adaptation to different core behaviors. Likewise, the gas-

Brayton thermal system can be tuned or swapped to reflect alternatives such as Rankine or Stirling cycles.

Because any part of the system can be simulated in real time, it can easily be reconfigured to incorporate both simulated and physical distributed energy assets and adapt to different microgrid topologies. This flexibility allows developers to test a wide range of configurations and control strategies before physical deployment, reducing risk and accelerating design iteration. This approach parallels the successful demonstration of using run-of-river hydropower for grid black start (Ojo 2023).

6 Research Targets and Goals

Current research targets are focused on developing comprehensive databases, models, and resources; conducting rigorous testing and demonstrations; and exploring use case applications to enhance the technology readiness of nuclear microgrids. These efforts aim to facilitate the integration of SRs into a broad range of microgrid configurations; addressing both electrical and thermal energy needs; and ensuring reliable, cost-effective, and sustainable energy solutions for a variety of applications. Additionally, consideration for standards and work towards public acceptance are also needed.

Figure 6 illustrates the framework developed for feasibility testing and demonstration of nuclear-powered microgrid applications. The process begins with a review of microgrid application requirements and alignment with technology characteristics, followed by energy system design and control development. This is followed by transient simulation, real-time hardware-in-the-loop testing, and ultimately lab-scale non-nuclear and nuclear field demonstrations. The nuclear-powered data center application will be demonstrated as the first NPM use case using MIB, MAGNET, and MARVEL at INL. The insights gained from this data center microgrid demonstration will be used to build a library of resources to support future demonstrations and eventual commercial deployments.

Below are specific goals and research targets:

Figure 6. Small reactor in microgrid feasibility and testing framework and research targets.

Database and Models and Resources:

- Create a comprehensive library of generic and specialized modeling and simulation resources that includes a cost estimation framework, various models (steady state, dynamic, neutronics, thermal hydraulic, mechanical, and electrical), optimization controls electromagnetic transient (EMT) simulations, real-time simulations, power conversion system designs, and energy storage configurations. This library will focus on all technology lines and key promising reactors and applications.
- Develop a library of design configurations specifically for small reactors in microgrid applications that address both heat and electricity needs. This resource will encompass the controls necessary to coordinate various technologies and outline strategies for operating microgrids in both grid-connected and islanded modes, covering thermal and electrical islands.
- Establish a database that includes information on nuclear technologies, fuel technologies, and relevant market applications for the most promising reactor technologies. This database will provide detailed technological characteristics, including cost, ratings, features, and operational data (such as ramp rates), to facilitate the preliminary selection and screening of technologies for specific applications.
- Build a generic testing platform using MAGNET and MIB to conduct control and power hardware-in-loop simulations, along with lab-scale non-nuclear testing. Additionally, utilize the MARVEL platform for small-scale nuclear microgrid demonstrations.

Integrated Control, Operation and Protection Coordination Framework

- **Integrated Control Framework:** Develop a generalized control framework for nuclear microgrids that coordinates nuclear, thermal, and electrical subsystems and enables real-time adjustment of heat and power outputs based on demand. The framework will align with IEEE microgrid control standards and NRC requirements for advanced reactors, incorporate autonomous control using AI/ML, and design subsystem control gains to maximize flexibility while maintaining safety. It will account for operational limits on magnitude and rate of change and define protocols for normal and emergency conditions. The framework will be validated through high-fidelity transient simulations and tested under extreme scenarios, including coolant accidents and major load rejections, using CHIL testing with the MACS/MAGNET system and physical experiments with MAGNET and MARVEL.
- **Operation Framework for Efficient and Safe Energy Management:** Develop a framework for optimal microgrid operation that coordinates electrical and thermal generation, loads, and storage based on asset-specific dynamics such as ramp

rates, minimum up/down times, and hold periods. The framework will maintain operating reserves and adaptive capacity to ensure resilience to major disturbances and accidents and will define strategies for both grid-connected and islanded operation.

- **Protection Coordination for Subsystems:** Develop a comprehensive protection framework that coordinates nuclear, thermal, and electrical protection systems to maintain situational awareness and safely manage significant transients originating in any subsystem. Designs will align with IEEE microgrid protection standards, NRC nuclear safety requirements, and ASME thermal safety standards. The methodology will define ride-through versus shutdown scenarios so that disturbances in one subsystem do not unnecessarily trip others or create safety risks, thereby enhancing overall resilience and enabling safe, seamless microgrid operation during transient events.
- **AI/ML-guided energy management systems:** Create a data driven framework to enhance adaptive control, operational optimization, system economics, reliability, and overall efficiency.

Testing and Demonstration:

- Demonstrate a non-nuclear test of the nuclear microgrid in the laboratory using MAGNET, MIB, and INL's HPC-in-a-Box (FY26 Target).
- Demonstrate the application of nuclear energy in both electricity-only and combined heat and electricity configurations using MAGNET, Thermal Energy Delivery System (TEDS), and MIB facilities. This will include demonstrating the operation and coordination of microgrid configurations (FY28 Target).
- Conduct a nuclear test of the nuclear microgrid using MARVEL, MIB, and HPC-in-a-Box (FY29 Target).
- Showcase the autonomous operation of the nuclear microgrid using MIB and MAGNET, followed by MARVEL and MIB. Develop an operational framework and controls for the supervisory management of the microgrid, encompassing both normal and abnormal operational scenarios. (FY30 Target).
- Validate nuclear-powered microgrid standards through appropriate modeling and simulation should be used to help develop the requirements to be included in the standards

Use Case Application Studies and Technology Readiness Timeline Development:

- Assess the operational and economic feasibility of integrating nuclear technology into various microgrid applications, using First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) estimates for different technologies. Key applications include:
    - DoD infrastructure and military base microgrids
    - Data Center Microgrids
    - Remote and island community microgrids
    - Mining and advanced manufacturing
    - Transportation Centers of the Future
    - Critical Infrastructure Microgrids
    - Industrial Facility Heat and Power Microgrids
    - Commercial Facility Microgrids
    - Rural electric cooperatives and small utilities
    - Space applications

Social and Regulatory Acceptance

The unique challenges and opportunities for deploying SRs within microgrids represent a critical knowledge gap. A strategic path for SR microgrid deployment should focus on addressing public acceptance and the social license to operate, including:

- Assess impacts on social service infrastructure, such as specialized emergency response training and security personnel, by engaging emergency planners and first responders to understand their cost, equipment, and training constraints.
- Examine microgrid deployment in harsh environments with unreliable grid access, accounting for regional, geographic, and environmental challenges as well as new obstacles introduced by SR technologies.
- Assess licensing, maintenance, liability, and fuel-cycle considerations for deploying SRs in sub-utility microgrids, creating an opportunity to gather stakeholder input for shaping implementation agreements and supporting resources.
- Address the lack of standardized microgrid permitting and the variability of state-level requirements, which together create a complex regulatory landscape that must be reconciled with the stringent rules governing nuclear operations.

Standards

To enable secure, compliant, and scalable deployment of SRs within microgrids, the following actions are recommended:

- Conduct a study to confirm that all required standards for SR-based power plants (at both distribution and transmission levels) exist and to identify gaps where standards are missing or incomplete, including those specific to SR integration in microgrids.
- Manufacturers of SR systems should be invited to participate in revisions of appropriate interconnection standards. Their participation would ensure that any SR-unique interconnection needs or characteristics are identified and properly considered when writing interconnection requirements.

Integrated Heat Applications

All nuclear reactors produce heat as a primary output. Electricity is usually the only output that is utilized, even though a large portion of the energy generated is discarded as waste heat. Microgrids offer the potential to utilize heat more effectively when direct-use heat applications are co-located. When combining electrical and thermal processes, the number of permutations of generation, storage and end-use increases exponentially, meaning that conventional design optimization processes are not adequate. The following research areas are recommended:

- Optimize SR thermal and electric output together using exergy-based methods to maximize efficient use of both primary and waste heat across diverse applications.
- Standardize thermal interfaces and storage systems through modular designs and validated storage configurations to simplify integration and maintain reactor safety margins.
- Develop high-fidelity models and validation strategies for coupled thermal–electric systems to assess dynamics, interactions, and tradeoffs, ensuring reliable and resilient microgrid performance.
- Develop real-time dynamic models of thermal and electric co-optimization
- Develop metrics to measure quantities like exergetic efficiency, reliability, robustness and cost, and develop optimization processes that utilize these metrics
- Develop decision-support tools that help designers navigate options
- Demonstrate pilot systems that integrate SRs with industrial processes

7 Why DOE?/DOE investment justification

Industry demand for DOE engagement is clear: as of August 2025, INL, on behalf of DOE, has received letters from eight microreactor developers, two application developers, and one electric utility urging DOE to advance application integration.

A significant opportunity exists to strengthen the connection between SR technology development and the grid-readiness planning needed for deployment. Expanding DOE OE and NE research in critical interfacing areas (e.g. thermal energy management and delivery, power conversion, and coordinated control) will help ensure SRs can be effectively integrated into future energy systems. DOE investment is therefore essential to build the knowledge base required for microgrid stakeholders to share responsibility with technology vendors, confidently assess integration pathways, and support the most promising SR technologies for future energy systems

The DOE is well positioned to tackle these challenges through the capabilities National Laboratory complex possesses, including but not limited to:

- INL maintains and operates key facilities which include the MARVEL microreactor project at the Transient Reactor Test Facility (TREAT) facility, National Reactor Innovation Center (NRIC)'s Demonstration of Microreactor Experiments (DOME) facility for novel reactor testing, Dynamic Energy Testing and Integration Laboratory (DETAIL), and Power and Energy Real-time Laboratory (PERL) for nuclear thermal and microgrid integration testing.
- The Sandia Holistic Advanced Reactor Capabilities Center (SHARCC) supports the deployment and long-term operation of advanced nuclear energy systems, enabling informed design, physical & cybersecurity, and safeguards & non-proliferation, safety, emergency response. Sandia's Molten Salt Test Loop (MSTL) is a unique industrial-scale testing capability that allows industry, government and academic researchers to test components in flowing, molten nitrate salts. Sandia also operates a >750 °C high-temperature/high-pressure flow loop to investigate halide and carbonate molten salts.
- Argonne National Laboratory (ANL)'s multidisciplinary capabilities in nuclear reactor design and control, microgrid and macrogrid modeling and simulation, electrical systems integration, industrial technologies, supply chains, and extreme weather and natural hazards modeling and resilience.
- National Laboratory of the Rockies (NLR)'s Advanced Research on Integrated Energy Systems (ARIES) platform for high-fidelity grid integration, co-simulation, and dynamic analysis,
- Pacific Northwest National Laboratory (PNNL)'s Energy Storage Materials Initiative (ESMI) and research in distributed energy control and grid-edge integration, and

- Savannah River National Laboratory (SRNL)’s expertise in nuclear operations training, human factors engineering, reactor systems testing, and Digital Real-Time Simulator (DRTS) development, using AI-guided and physics-informed approaches, can directly support SR deployment. These capabilities are critical for workforce preparation, validating integrated microgrid applications, and advanced hardware-in-the-loop (PHIL) testing with Grid-forming inverters. SRNL’s PHIL infrastructure, including a 230 kV tap that provides step-down voltages at 115 kV, 69 kV, 34.5 kV, and 13.8 kV, enables comprehensive, realistic evaluation of SR integration into various grid architectures.
- Lawrence Livermore National Laboratory (LLNL)’s power grid modeling and national security expertise supports SR deployment and power grid resilience. LLNL hosts the Skyfall laboratory, a combined cyber–physical hardware-in-the-loop test bed, which enables detailed co-simulation of energy sources within microgrids designed for critical infrastructure such as military bases, emergency response hubs, and remote facilities. These data can be combined with capacity expansion planning models, such as LLNL’s power grid capacity expansion model for modeling both grid-wide and micro-grid specific SR deployment strategies.

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