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Revision 0

Net-Zero Microgrid Program Project Report:

Small Reactors in Microgrids

July 2023

Technology Modeling and Selection

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The Net-Zero Microgrid Program provides cross-cutting research to accelerate the use of renewable and zero-carbon generation in microgrids.

Idaho National Laboratory

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EXECUTIVE SUMMARY

This report presents a detailed model for small reactors (SRs) in microgrids, identifying cost and operational data sets for various SR technologies suitable for different microgrid applications. It articulates a path forward for technoeconomic studies of SR in microgrids and the selection of SR technology suitable for different applications and deployment scenarios.

This report demonstrates the capabilities of the net-zero microgrid (NZM) Xendee platform for modeling an SR module with electricity, heat extraction and thermal storage in microgrids configurations. The model effectively captures the most important technical and economic considerations for SR technology specific analysis: cost and operational characteristics of SR technology and financial costs and incentives. The model can analyze multiple scenarios to establish metrics for cost-competitive and zero-carbon microgrids connected to the grid or completely isolated. The model is fully integrated within the Xendee platform for modeling and analysis of clean energy microgrids with storage and generation from renewable energy sources. The model captures the capabilities, constraints, and nuances of SR by incorporating parameters related to plant economics, design efficiency and performance, plant operation and component and fuel lifespan, as shown in Figure ES 1 below.

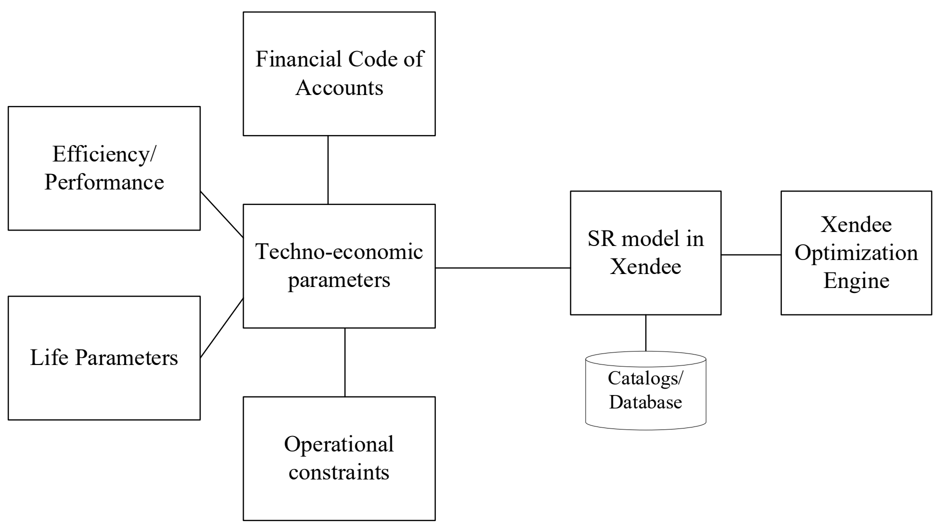

Figure ES 1. External module for producing and importing SR catalog in Xendee.

The cost and operational parameters modeled in the SR module are specific to the technology selected for integration in the microgrid. Cost parameters recognize advanced nuclear technology for modular production and installation based on economies of scale from factory manufacture and related commissioning, and cost reduction through technology maturation—first-of-a-kind (FOAK) and *nth*-of-a-Kind (NOAK). The cost parameters include installation, operations and maintenance (O&M), fuel refueling cycle, and reactor life. Installation cost reflects economies of scale due to unit sizing at scale and colocation. O&M economies of scale for both fixed- and variable-cost fuel life-cycle costs are incurred at every refueling interval, with separate front- and back-end fuel costs, as well as waste-handling and disposition costs.

This report investigates key characteristics of different SR technologies suitable for microgrid applications, including design principles, sizing, coolant properties, temperature ratings, fuel structures, and life-cycle considerations. This also includes fuel technologies applicable to these SR systems, alongside strategies for nuclear-waste and spent-fuel management and approaches to address safety, security, and proliferation challenges. Four primary groups of SR technologies are examined: water-cooled, liquid-metal-cooled, high-temperature gas-cooled, and molten-salt-cooled systems.

In this report, an initial guideline for technology selection is established, aligning the characteristics of the technologies with the requirements of microgrids. The selection of technology in a microgrid is influenced by various factors, including financial capacity, location and accessibility, demand type and characteristics, reliability and resilience requirements, area constraints, and the lifespan of the microgrid. The types of electrical and non-electrical applications within the microgrid also play a significant role in technology selection. The characteristics of SRs, such as their smaller size, modularity, transportability, long refueling interval, improved safety features, ability to operate in autonomous or semi-autonomous mode, and provision of high-grade heat, are particularly appealing for microgrids. Furthermore, a list of considerations for implementing SRs in microgrids is outlined.

The SR model is created to be continuously improved with the acquisition of actual data on investment and operational costs, experience with supply chains, production at scale, and field deployments. In the near term, performance data on applications in microgrids will become available from lessons learned from laboratory tests, such as those planned for the Microreactor Applications Research Validation and Evaluation Project (MARVEL), led by Idaho National Laboratory (INL).

The SR model incorporates scenario data and known SR design specifications, enabling technoeconomic analysis for SR deployment in microgrids. It specifically considers the distinctive attributes of SRs as generators in technoeconomic studies. SRs can be modeled and analyzed with generation from renewable-energy sources, energy storage, and flexible loads over a range of functionality and applications. This offers a comprehensive tool for feasibility studies, scenario development, and sensitivity analysis for “what-if” consideration of any range of assumptions about SRs in microgrids and other aggregations of distributed-energy resources, including virtual power plants.

This report is a product of the NZM Program[a] at Idaho National Laboratory, supported by the Department of Energy (DOE), Office of Electricity (OE) Microgrid Program. The NZM Program recognizes SRs as a carbon-free energy source for electricity and heat generation necessary for microgrids to transition away from carbon-fuel-based generation that is prevalent in today’s microgrids. The generation, storage, and application elements of a net-zero microgrid are depicted in Figure ES 2. .

[a] Net Zero Carbon Microgrids, INL, 2021 https://www.osti.gov/biblio/1831061

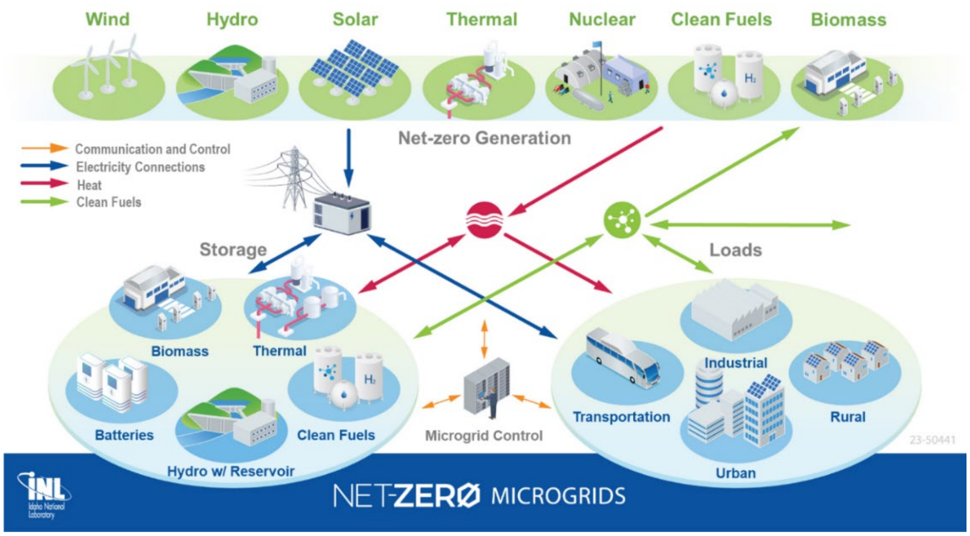

Figure ES 2. The elements of a Net-zero microgrid.

ACKNOWLEDGMENTS

We thank Dan Ton, program manager for the DOE Office of Electricity Microgrid Program for supporting the effort that produced this report. We appreciate the review and comments from John Jackson, national technical director of DOE Office of Nuclear Energy Microreactor Program and Thomas Mosier, group lead of Energy Systems Group at INL.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

ARIS	Advanced Reactors Information System
CANDU	CANada Deuterium Uranium
CHP	Combined heat and power
CREIPI	Central Research Institute of Electrical Power Industry
DoD	Department of Defense
DOE	Department of Energy
DRG	Deep geological repository
EBR	Experimental Breeder Reactor
EMS	Energy-management system
EPIC	Energy Policy Institute at Chicago
FC	Frequency control
EPZ	Emergency planning zone
FOAK	First of a kind
GHG	Greenhouse gas
GIS	Geographic information system
HALEU	High-assay low-enriched uranium
HEU	Highly enriched uranium
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
iPWR	Integral pressurized water reactor
LBE	lead-bismuth eutectic
LEU	Low-enriched uranium
LF	Load following
LWR	Light-water reactor
MACRS	Modified Accelerated Cost Recovery System
MARVEL	Microreactor Applications Research Validation and EvaLuation
MoveluX	Mobile-very-small reactor for local utility in X-mark
MSR	Molten-salt reactor
NERAC	Nuclear Energy Research Advisory Council
NETL	National Energy Technology Laboratory
NOAK	n^{th} of a kind

NPP	Nuclear power plant
NZM	Net-zero microgrid
O&M	Operations and maintenance
OPEX	Operational expense
PCM	Phase-change material
PWR	Pressurized water reactor
PV	Photovoltaic
RPV	Reactor pressure vessel
SMR	Small modular reactor
SR	Small reactor
TES	Thermal-energy storage
TRISO	TRi-structural ISOtropic
TRU	TRansUranic
UNIST	Ulsan National Institute of Science and Technology
VPP	Virtual power plant

1. INTRODUCTION

The objective of this report is to introduce the small reactor (SR) model that has been incorporated into the Xendee microgrid planning and design platform and provide technology-selection guidance for SRs in diverse microgrid applications and deployment scenarios. Idaho National Laboratory (INL) and Xendee co-developed the SR model and are disseminating it through the Xendee platform. With this tool and information, microgrid planners can consider the viability of SRs alongside other clean generation technologies for any application that requires heat and power. The report examines the technical and operational characteristics of SRs being developed across different technology lines, laying the groundwork for technoeconomic modeling and analysis.

A microgrid is defined by the Institute of Electrical and Electronics Engineers (IEEE) 2030.7-2017, "IEEE Standard for Specification of Microgrid Controllers," as:

> *A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that act as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected and island modes* [1].

Microgrids are emerging as a viable clean solution for addressing diverse energy needs, ranging from remote communities and islands to congested urban areas [2]. The integration of SRs—smaller-size fission-reactor technologies designed for smaller applications—within microgrid systems is an attractive option for decentralized power generation [3],[4]. The SRs that would be of interest to the scale of microgrids range from 100 kW to 100 MW that would be encompassed by reactors referred to as microreactors and small modular reactors (SMRs).

Historically, smaller-sized nuclear reactors were primarily used for naval and research purposes. However, the emergence of advanced SRs brings increased flexibility in terms of siting and operation, enabling their use in meeting energy demands [5]. The modular nature and advanced safety features of SRs make them attractive to countries with smaller grid sizes with no prior nuclear experience [4], [6]. Furthermore, the modular and transportable components enable their factory production, significantly reducing construction time and cost while standardizing deployment and operation [7]. The ability to deploy SRs in remote, off-grid communities enhances access to clean electricity and heat, addressing energy poverty in such areas. These advantages align seamlessly with the concept of floating power plants based on SRs, which can provide sustainable energy solutions for coastal or island regions. One of the key advantages of SRs is their long-lasting nuclear fuel, which enables independent operation for extended periods without the need for external fuel supplies [8]. This characteristic is particularly beneficial for microgrid communities with limited access to the central transportation network, such as remote communities and islands.

SRs are being developed on various reactor-technology lines, including water-cooled reactors, high temperature gas-cooled reactors, liquid metal-cooled fast-neutron-spectrum reactors, and molten-salt reactors [5]. These technologies are different in terms of their design principles, sizing, coolant properties, temperature ratings, fuel structures, and life-cycle considerations. These technologies can adopt a variety of thermal and electrical configurations with energy-storage and coupled-heating applications alongside power-generation engines. The technology and thermal configurations can be adopted for a microgrid, depending upon the mission that microgrid is designed to serve.

The smaller size, modularity, long-lasting fuel, and diverse heat applications offered by SRs make them well-suited for microgrid deployment. However, there are still several challenges that must be addressed concerning technology, deployment, and the supply chain. These include considerations such as control-room staffing and human-factor engineering for multimodule plants, the adaptability of existing codes and standards, manufacturing approaches for novel components, and back-end solutions for fuel-cycle management [5], [9]. The technical and economic challenges of operating SR technologies under variable power-system operating conditions in microgrids and alongside renewables need to be addressed [10]–[12]. Industry and regulatory bodies are actively engaged in ongoing discussions and deliberations to tackle these challenges related to the implementation of SRs in microgrids.

The report is structured into five sections, with one appendix provided. The following are brief descriptions of the contents of each section.

Section 2 describes the SR model developed within the Xendee platform. The SR model is designed to incorporate financial and operational parameters, enabling the characterization of nuclear technology for microgrid technoeconomic studies. The model captures unique features of SRs, including fuel-cycle approach with front-end and back-end processes and longer-refueling period, economies of scale in investment and operation cost, provision of electricity and high-grade heat, and reactor-maneuvering approach for baseload and semi-baseload operations. The model allows for the analysis of multiple scenarios, establishing metrics for cost-competitive and zero-carbon microgrids that are either grid-connected or completely isolated, incorporating storage and renewable energy resources. Section 2 also presents the results of a case study that considered SR and thermal-energy storage (TES) to meet the electricity and heating requirements of a microgrid.

Section 3 discusses the most-promising SR technologies suitable for microgrid applications, with a specific focus on their design principles, sizing, coolant properties, temperature ratings, fuel structures, and life-cycle considerations. It delves deeper into new fuel technologies that can be used in SRs, strategies for managing nuclear waste and spent fuel, and approaches to address safety, security, and proliferation challenges. Furthermore, a range of power-conversion systems applicable to SR technologies are explored, bridging the knowledge gap between reactor technology and microgrid planners. Similarly, various thermal-design configurations and TES options are considered to facilitate optimal heat generation, extraction, use, and storage within the microgrid system to support various electrical and non-electrical applications. Based on this analysis, an initial guideline for technology selection is established in Section 3, aligning the characteristics of the technologies with the requirements of microgrids. The characteristics of SRs, such as their smaller size, modularity, transportability, long refueling interval, improved safety features, ability to operate in autonomous or semi-autonomous mode, and provision of high-grade heat, are particularly appealing for microgrids.

Section 4 delves into microgrid-technology selection, considering key factors that influence the decision-making process. These factors include financial capacity, location and accessibility, size, demand type and characteristics, reliability and resilience requirements, area constraints, and the lifespan of the microgrid. A microgrid may have considerable heating demand, which can play an important role in deciding thermal- and electrical-generation assets, particularly in relation to selecting suitable SR technologies for specific applications. The section concludes by providing a comprehensive list of considerations for implementing SRs in microgrids.

Section 5 concludes the report by presenting potential future work, which includes enhancing the SR model to incorporate multiple grades of heating applications and creating a modeling catalog for the most-promising SR technologies that can be accessed by the Xendee platform. Future case studies are identified, focusing on design and application aspects of SR in microgrids. On the design side, studies will be carried out to optimize the selection of power-conversion systems and TES technologies, including retrofitting existing technologies for advanced SRs. On the application side, studies will be carried out to examine the price target and timeline for SR technology to achieve cost competitiveness against natural-gas generators and other technologies in different microgrid markets. Additionally, the role of SRs in addressing reliability and resilience issues, such as transmission congestion, through virtual power plants will be explored.

Section 6 contains the bibliography, which includes the list of references cited in this report. Appendix A consists of two subsections: the first describes the list of parameters included in the SR model, while the second presents the list of SR models suitable for microgrid applications, as reported by the International Atomic Energy Agency (IAEA).

2. SMALL REACTOR TECHNOECONOMIC MODELING

2.1 Model Overview

SRs are advanced nuclear reactors that have unique cost and operational characteristics that differentiate them from other generation technologies commonly employed in microgrids. These characteristic features include, but are not limited to, extended refueling cycles, decommissioning costs, modes of power variation, and combined heat and power (CHP) operations. These need to be recognized when modeling them as generators in microgrids. These must be accounted for in microgrid dispatch and planning decisions as these interact with loads, storage, and other generation technologies. To model these interactions within a microgrid decision-support platform, an SR model has been added to the Xendee platform.

Xendee is an informed technoeconomic decision-making platform built on well-established scientific models of microgrid-power and energy behavior modeling [13]. It captures steps needed to design and implement microgrids, community energy projects, and distributed energy resource projects for optimal planning and operation dispatch strategies in the context of multi-energy systems. Xendee provides the optimal planning and operation dispatch of microgrids by guaranteeing the reliability, resilience, and practical boundary conditions of such projects.

The SR model in Xendee inherits features of such conventional generation technologies as unit-install costs, minimum loading, and ramp-rate limits. However, the following unique features are added:

- Fuel cost every refueling period
- Decommissioning cost after the SR lifetime
- Option for baseload operation of the electricity generators
- Electricity and heat output that can be traded
- Reactor power maneuvering—cycling limits.

Inputs for these unique features are highlighted by green boxes in the screenshot of the SR input data interface in Figure 2-1. Input for features that are common to other microgrid technologies modeled in Xendee are described in Section 2.7.

2.2 SR Unique Features

2.2.1 Fuel Cost

Unlike other generation sources that rely on continuous fuel supplies (such as gas generators), nuclear fuels can last significantly long periods. Therefore, refueling in nuclear power plants occurs at discrete time intervals with distinct front- and back-end processes. The fuel cost is therefore defined by front- and back-end costs. Figure 2-1 shows the SR specification entry form. The front-end fuel cost encompasses all the expenses related to loading nuclear fuel, including the cost of natural raw uranium and the costs associated with conversion, enrichment, fabrication, and fuel loading [3]. On the other hand, back-end fuel cost refers to the expenses associated with handling spent fuel and nuclear waste, which includes interim storage, transport, and disposal [3]. The front-end fuel cost is added to the capital expense as part of the investment-year costs. Succeeding fuel costs are part of the operational expense (OPEX). Front- and back-end costs are incurred after every refueling period.

2.2.2 Decommissioning Cost

The decommissioning cost of a nuclear plant encompasses the expenses involved in dismantling the facility after its operational lifespan has ended. These costs typically encompass expenses related to the shutdown of the reactor, repurposing the facility, and demolition activities [3]. Additionally, it encompasses the final instance of the back-end fuel cost incurred at the end of the SR's last refueling interval.

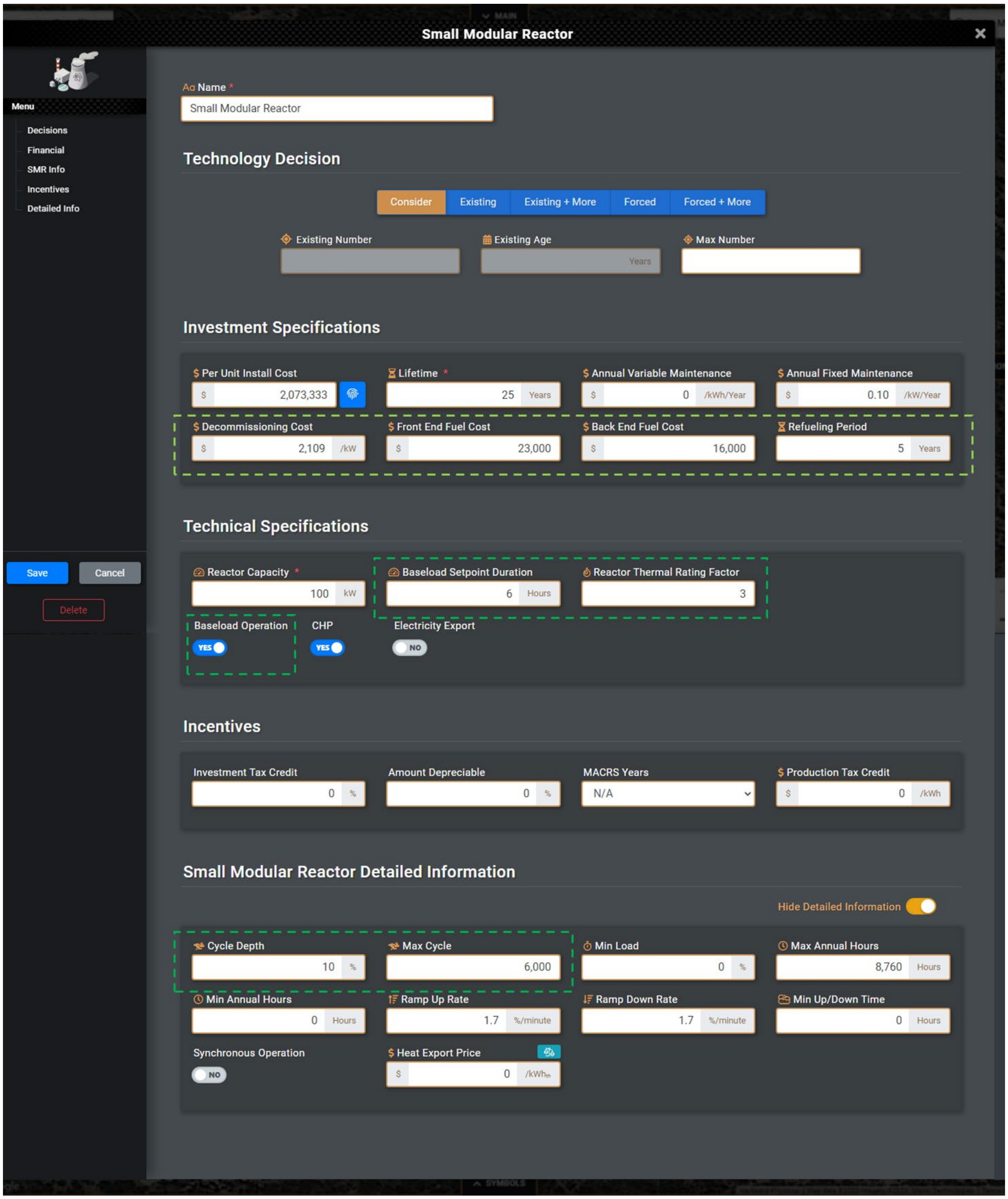

Figure 2-1. SR specification form in Xendee, as of June 2023.

2.2.3 Baseload Operation

Considering high initial costs and technical limitations associated with power variations, it may be preferred to operate SRs in baseload operation mode, even in microgrid applications [11], [14]. The baseload operation mode can be explicitly enabled in the SR module. With baseload operation, the generator maintains a specific output level for a specified period of time before another operating level can be set [15]. This operation mode is defined by the equations below.

$$elec_{\mathrm{t}} - elec_{\mathrm{t-1}} \leq bchange_{\mathrm{t}} \cdot \mathrm{M}$$

$$elec_{\mathrm{t-1}} - elec_{\mathrm{t}} \leq bchange_{\mathrm{t}} \cdot \mathrm{M}$$

$$\sum_{(\mathrm{t}-(\mathrm{minBL}-1)) \leq \mathrm{h} < \mathrm{t}} (1 - bchange_{\mathrm{h}}) \geq bchange_{\mathrm{t}} \cdot (\mathrm{minBL} - 1)$$

where

t	set pertaining to the time step
M	a very large number
minBL	minimum duration at a set point, Baseload Setpoint Duration that is > 1
$bchange_{\mathrm{t}}$	binary variable to denote a change in the output power at time step t
$elec_{\mathrm{t}}$	non-negative variable for the generator output at time step t.

The first two equations define the binary variable, $bchange_{\mathrm{t}}$, that is equal to 1 whenever there is a change in the output power between the current and previous time step. The third equation enforces that to have a change in the output power at time step t, there should be no change in output power in the previous minBL time steps.

2.2.4 Electricity and Heat

Depending on its design, an SR can incorporate multiple heat-extraction points, effectively operating as a combined heat and power (CHP) system. The quality of the extracted heat is determined by these multiple heat-extraction points. The process heat obtained directly from the SR's secondary system is considered high-grade heat because it is at a high temperature suitable for applications requiring elevated temperatures, such as high-temperature electrolysis. On the other hand, heat extracted from intermediate stages and the exhaust of turbines are categorized as mid- and low-grade heat, respectively, due to their lower temperatures. These different grades of heat serve various purposes depending on their temperature range, allowing the SR to efficiently meet a wide range of application needs and optimize its overall energy efficiency.

In this first Xendee release that contains an SR model, heat is assumed to be extracted from the first extraction point at which it can be used for electricity generation, high-temperature heat end-use, or both. Future versions will contain multiple heat grade-level modeling. For now, this means that electricity and heat generation is a tradeoff as defined below for one unit of an SR.

$$elec_{\mathrm{t}} + heat_{\mathrm{t}} = reactor_{\mathrm{t}}$$

$$elec_{\mathrm{t}} \leq ER$$

$$reactor_{\mathrm{t}} \leq TR$$

$$TR = ER \cdot \mathrm{RTRF}$$

where

RTRF	Reactor thermal-rating factor

ER	electricity rating, max electricity generation
$heat_t$	non-negative variable for usable heat generation at time step t
$reactor_t$	non-negative variable for reactor power at time step t
TR	thermal rating, max heat generation.

The thermal-rating factor of a reactor is defined as the ratio between its electricity and thermal power ratings. It is a reciprocal of the net electrical efficiency, which considers both the efficiency of the thermodynamic cycle and the efficiency of the turbine and generator. For example, an SR with 5 MWe/15 MWth rating has a reactor thermal-rating factor = 3. This factor defines the max reactor power. Note that if CHP is disabled, the reactor power is used only for electricity generation.

2.2.5 Reactor Power Maneuvering—Cycling Limits

Power maneuvering of the SR is constrained by the cycling limits in reactor power throughout the SR lifetime. To estimate cycling limits, the sum of the changes in reactor power is computed. The total change is then limited based on the cycle depth and the annual max cycles. The cycle depth defines one cycle and is the percentage of the SR thermal rating. For example, a 10% cycle depth for a 300 kWth SR has one cycle equal to 30 kWth. The annual maximum number of cycles is the max cycles in the SR datasheet, divided by the lifetime in years. A 25-year SR with 6000 max cycles will have 240 annual max cycles. If one cycle is 30 kWth, then the total changes in reactor power in a year should not exceed 7,200 kWth. This approximation of the reactor's power-maneuvering limit is characterized by the formulation below.

$$|reactor_t - reactor_{t-1}| = delta_t$$

$$\sum_t delta_t \leq AMC$$

$$AMC = TR \cdot \mathrm{CD} \cdot \mathrm{MaxCyc} / \mathrm{Lt}$$

where

CD	cycle depth, percent of thermal rating considered as one cycle
Lt	SR lifetime in years
MaxCyc	max cycle for the SR lifetime
AMC	max number of changes in reactor power in a year
$delta_t$	change of reactor power at time step t.

2.3 SR Model Demonstration

The SR model is demonstrated by three hypothetical cases (Table 2-2). Case 1 is a grid-tied system with electricity-only load and SR considered as an option. SR parameters and utility electricity rates are in Table 2-2 and Figure 2-2 respectively [16]. The energy rate is purposely set high to ensure SR investment. This can also be representative of an off-grid system with electricity from a diesel generator instead. Electricity rates are lower in Period 2 for Case 2 and 3 to create a possible scenario for electricity and heat-output tradeoff. Moreover, the electricity load is represented by a midrise apartment profile with 808 kW annual peak demand. Different combinations of enabled baseload operations and cycling limits on SR are tested to analyze the impact on the optimization results.

Table 2-1. Microgrid cases to demonstrate the SR model.

Case	Energy Source	Load	Technology to Consider in Xendee
1	Grid-Tied	Electricity	SR
2	Grid-Tied, Existing Boiler	Electricity, Heating	SR
3	Grid-Tied, Existing Boiler	Electricity, Heating	SR, Heat Storage

Table 2-2. SR parameters.

Parameter	Value
Unit Reactor Capacity	100kW
Per-Unit Install Cost	$2,073,333
Lifetime	25 years
Decommissioning Cost	$2,109/kW
Per-Unit Front-end Fuel Cost	$23,000
Per-Unit Back-end Fuel Cost	$16,000
Refueling Period	5 years

Case	Period1	Period2
1	$0.3832/kWh	$0.3832/kWh
2	$0.3832/kWh	$0.0500/kWh
3	$0.3832/kWh	$0.0500/kWh

Figure 2-2. Assumed utility rates with time-of-use rates for Case 2 and Case 3.

Case 2 is based on Case 1, with an existing boiler and heating load. The heating load is represented by full-service restaurant profile with a 900 kWth annual peak demand. Case 3 is based on Case 2, with an additional heat-storage investment option. Figure 2-3 illustrates Case 3 with a locational context as rendered in the Xendee geographic information system (GIS) view.

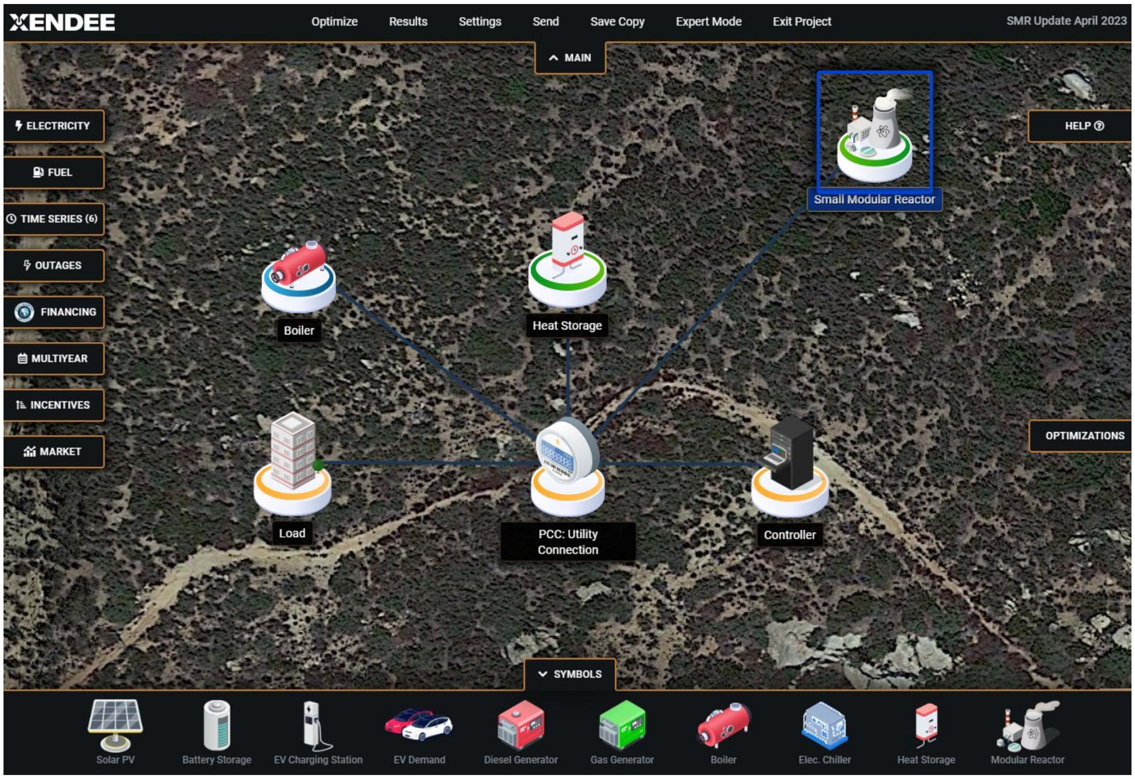

Figure 2-3. Xendee model for hypothetical microgrid Case 3.

Case 1 optimization results are shown in Figure 2-4 and Figure 2-5. The reference case is for a configuration without SR. The optimal investment capacity for the SR, with cost minimization, is 300 kW. Compared with the reference case, the optimal investment scenario saves 31% of energy costs and reduces CO_2 emission by 42%. Figure 2-5 shows the investment and decommissioning costs and the microgrid OPEX. The decommissioning cost is after a 25-year lifetime. The increase in OPEX due to the SR fuel can be observed every year after 5 years. For simplicity, it is assumed that an SR reinvestment occurs after the SR lifetime. This shown by the reinvestment cost in year 25.

	Total Annual Energy Costs (dollars in thousands)	Total Annual CO_2 Emissions (metric tons)
Reference	$2,214.5	2,518
Investment scenario (incl. annualized capital costs and electricity sales)	$1,530.7	1,466
Total Savings (%) (incl. annualized capital costs and electricity sales)	30.9 %	41.8 %

Type	Total New Capacity	Technology (New Capacity)
	300 kW	Small Modular Reactor (300 kW) (3 units)

Figure 2-4. Case 1 sizing result (with cycling limit, baseload operation not selected).

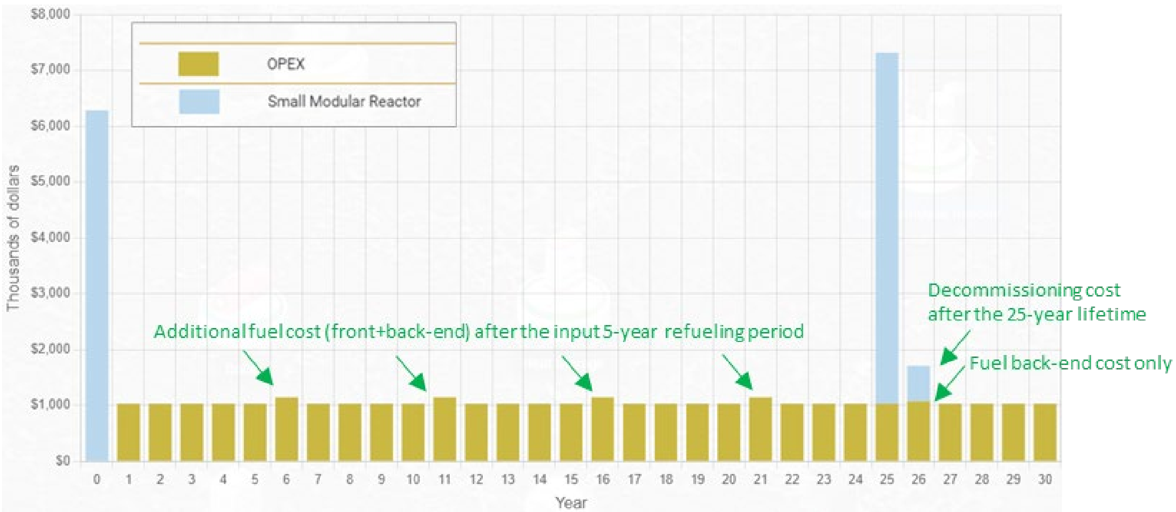

Figure 2-5. Case 1 general cost projection: 25-year lifetime SR with 5-year refueling period.

Figure 2-6–Figure 2-8 show the optimal dispatch for an SR with three assumptions: i) with cycling limit and without explicit baseload operations enabled, ii) without cycling limit and with baseload operations enabled, and iii) without cycling limit, without explicit baseload operations enabled. Electricity from the utility is removed from the chart to highlight SR dispatch. With the cycling limit, the optimum dispatch is similar to baseload operations because changes in power setpoint are limited. Without the cycling limit but with baseload operations enabled, there is more flexibility in power-setpoint changes, and the optimum size is higher. Without cycling limit and baseload operations, the SR can follow the load if it is the cost-optimal strategy, limited only by the installed capacity.

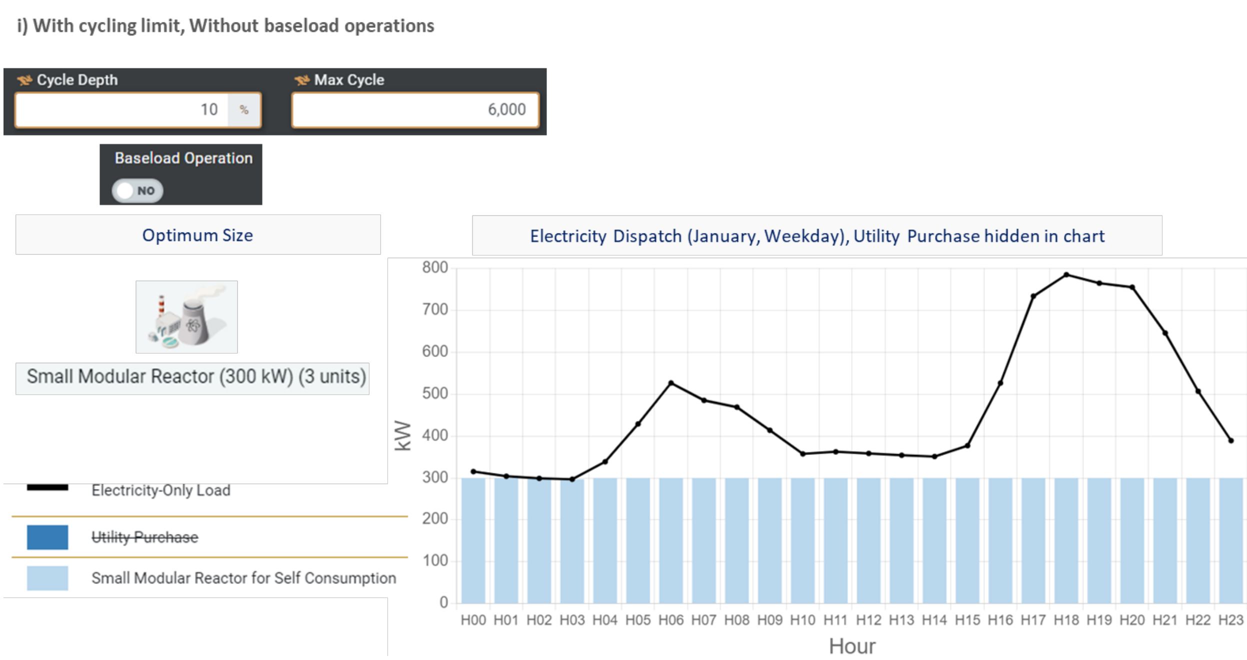

Figure 2-6. Case 1 dispatch with cycling limit, disabled baseload operations.

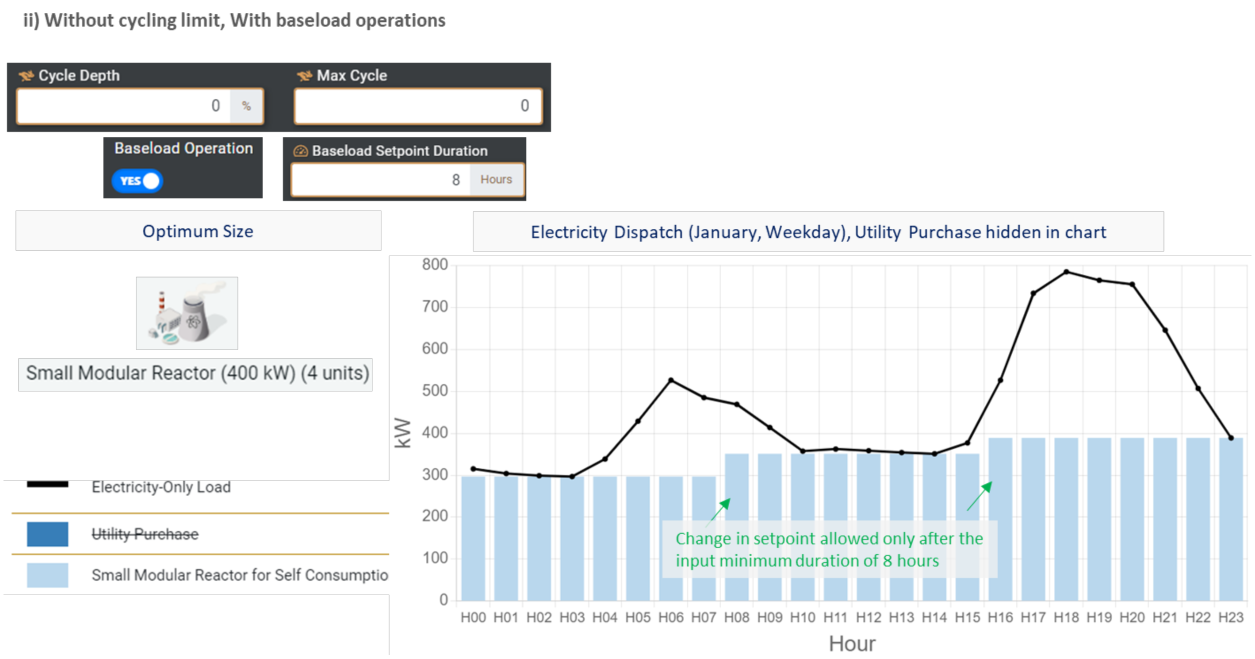

Figure 2-7. Case 1 dispatch without cycling limit, enabled baseload operations.

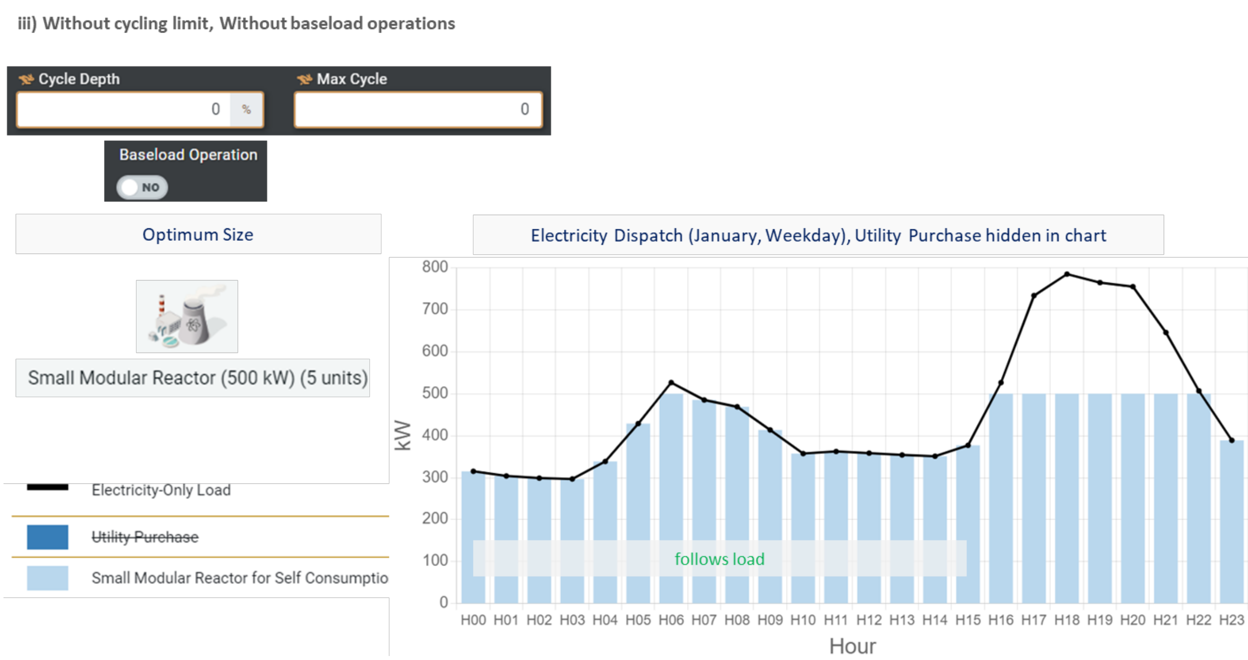

Figure 2-8. Case 1 dispatch without cycling limit, disabled baseload operations.

For **Case 2**, SR CHP is enabled with a reactor thermal-rating factor of 3. The utility energy rate is also reduced to $0.05/kWh from 12 midnight to 10 AM, as previously shown in Figure 2-2. Optimization results for Case 2 are shown in Figure 2-9. Between 7 AM and 10 AM, all electricity is from the utility. The SR generates no electricity, only heat. This suggests that it is cheaper to purchase electricity than natural gas for heat from the utility on the said time span. As such, the cost-optimal strategy is to use the SR as a heat source, rather than an electricity source, during this period. However, between 10 AM and

12 midnight, minimal heat is drawn from the SR because higher savings can be incurred if the SR generates electricity to reduce purchase from the utility.

At first glance, an SR should be able to supply all the heat most of the time because the reactor thermal rating is 900 kWth. However, the reactor cycling limit does not allow large changes in reactor power. Thus, reactor power does not reach the heating load, and heat is still drawn from the boiler. While this is not shown in the results in Figure 2-9, no cycling limit allows the SR to satisfy all of the heating load, except during times when both the electricity and heat demand are high.

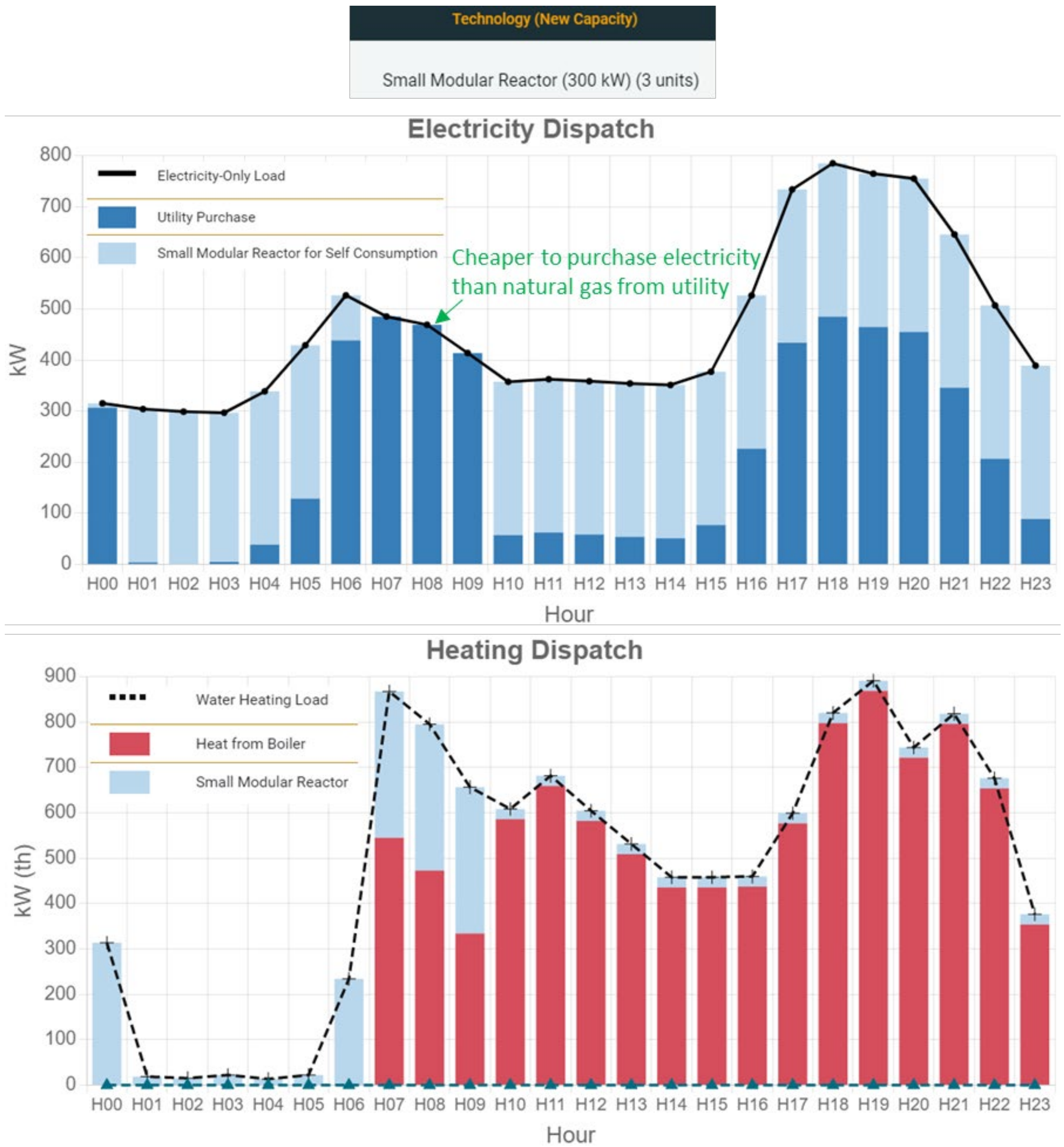

Figure 2-9. Case 2 optimal size and dispatch (January weekday): SR with heating load.

For **Case 3**, where heat storage is considered and installed, heat from the boiler is not needed. Because of its heat-storage capability, an SR can generate both high electricity and high heat while satisfying cycling limits. The result is shown in Figure 2-10. Heat is stored before 7 AM when the heating load is low. This means that the SR need not drastically decrease or increase its reactor power when the heating load fluctuates, as would be necessary in Case 2. Also, in contrast with the dispatch in Case 2, the

SR generates heat and electricity even during the period with low electricity rates. Because of greater flexibility in the SR dispatch, the optimal SR size at 400 kWth is higher than in Case 2, which is 300 kWth.

Technology (New Capacity)
Heat Storage (2.7 MWh_{th})
Small Modular Reactor (400 kW) (4 units)

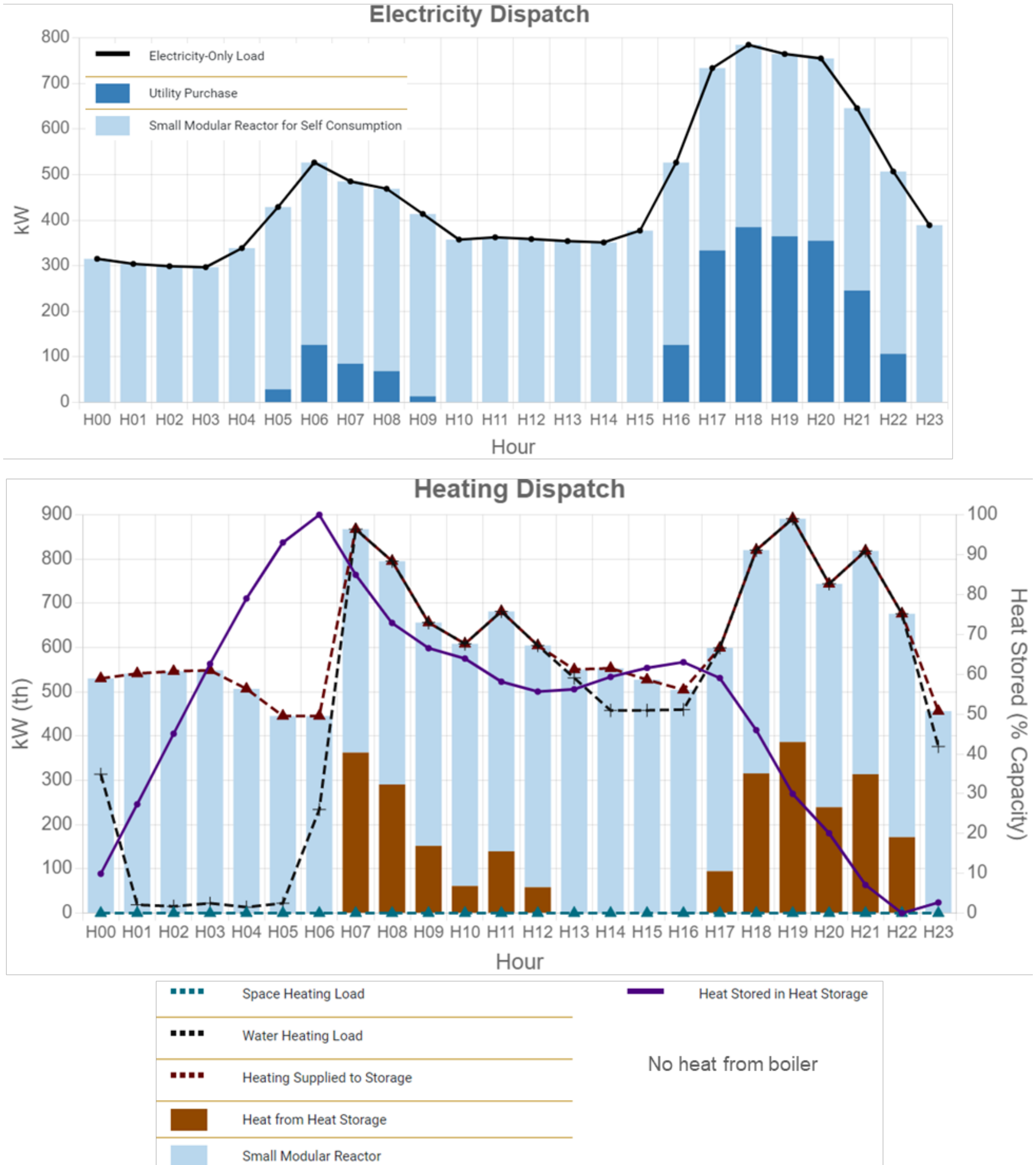

Figure 2-10. Case 3 optimal sizes and dispatch (January weekday): SR with heating load and heat-storage option.

2.4 Parameter Development and Integration

The SR model uses generalized parameters to represent all SR technologies. These parameters are influenced by various factors that depend on the specific type of reactor technology under consideration. They are calculated using raw design information, taking into account the unique design characteristics and requirements of each individual reactor technology.

To facilitate this process, a functionality will be developed that takes the raw information of SR technologies as inputs and calculates the parameters directly usable in the SR model. The reactor design specification parameters can be provided directly by reactor vendors and manufacturers, or imported from the IAEA's Advanced Reactors Information System (ARIS) tool [17]. The ARIS tool is regularly updated based on publicly available information on SR technologies. Figure 2-11 illustrates the steps involved, along with the list of raw information and SR parameters to be calculated using this functionality. Using this functionality, a SR database will be developed for the most-promising SR technologies.

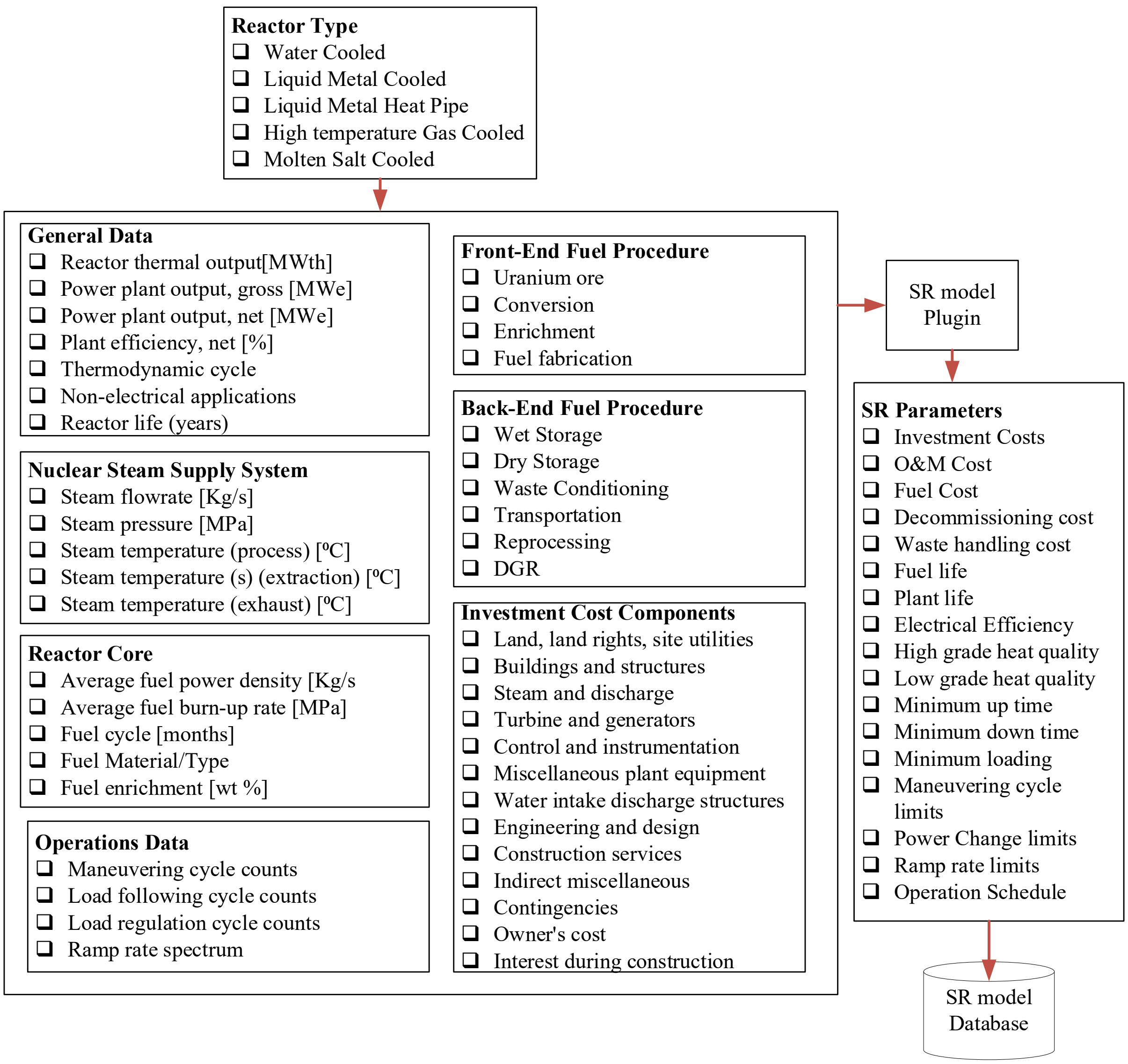

Figure 2-11. External module to produce parametric inputs for SR models to build the SR modeling database.

2.5 Xendee Model Features—Common to All Microgrids

The parameters shown in the SR input data interface in Figure 2-1 are listed below, with their descriptions. This includes other parameters in the SR model that are also common to other microgrid technologies. Parameters that are unique to the SR model, as of April 2023, are tagged accordingly and are discussed in the previous section.

Investment specifications:

- Per-Unit Install Cost: cost to buy and install the technology
- Lifetime: expected lifetime of the technology in years
- Annual Variable Maintenance: annual variable O&M costs per kilowatt hour
- Annual Fixed Maintenance: annual O&M costs independent of output
- Decommissioning Cost [Unique to SR]: cost when the SR reaches its lifetime
- Front-End Fuel Cost [Unique to SR]: cost of the nuclear fuel and its loading to the reactor core per unit of SR
- Back-End Fuel Cost [Unique to SR]: nuclear waste-handling cost that is incurred during refueling and at the end of the SR lifetime
- Refueling Period [Unique to SR]: number of years before the nuclear fuel is replaced.

Technical specifications:

- Reactor Capacity: rated operating power in kilowatts
- Baseload Operation [Unique to SR]: explicitly enable baseload operation; the alternative is load following
- Baseload Setpoint Duration [Unique to SR]: minimum amount of time before the generator power setpoint can be changed
- CHP: combined heat and power capability
- Reactor thermal-rating factor [Unique to SR]: the factor of thermal power relative to the electrical rating; for example, a factor of 3 on a 5 MW reactor will mean there is 15 MWth energy possible if all is used for heat
- Electricity Export: enable electricity export to the utility.

Incentives:

- Investment Tax Credit: federal tax credit for the technology
- Amount Depreciable: depreciation of property in modified accelerated cost-recovery system (MACRS)
- MACRS Years: recovery period for MACRS
- Production Tax Credit: An incentive associated with the production of energy.

SMR detailed information:

- Cycle Depth [Unique to SR]: the step-load increase or decrease in percentage of full electricity and heating-power capacity that is considered as one cycle
- Max Cycle [Unique to SR]: total number of load changes defined by the cycle depth that the reactor can withstand during its lifetime

- Min Load: the minimum load at which a technology can operate, introduced as a share of the nameplate capacity
- Max Annual Hours: maximum number of hours a technology can operate within a year
- Min Annual Hours: minimum number of hours a technology must operate within a year
- Ramp-Up Rate: the maximum increase in output power per minute
- Ramp-Down Rate: the maximum reduction in output power per minute
- Min Up/Down Time: minimum number of continuous hours that the technology must operate before it can shut off, or must be off before it can start up
- Synchronous Operation: enable all units to operate together instead of turning on and off individually
- Heat Export Price: the price per kilowatt thermal at which excess heat can be exported.

2.6 SR Development Cost Targets—Breakeven Install Costs

Xendee's optimizations can be used to calculate a breakeven "per-unit install cost" for SRs in microgrids in different configurations, applications, and locations. In this way the cost for the proposed SR that is economically viable within a certain microgrid configuration can be determined. The optimization can evaluate the maximum install cost for SRs in different configurations in the microgrid. Thus, the optimization will give a SR a cost that makes sense.

This speaks directly to the economic viability and financial attractiveness of an SR in any microgrid configuration or application. Many assumptions and parameters can affect viability other than the unit-install cost. Thus, the approach to be taken is to perform sensitivity analysis of the unit-install cost under different scenarios and technology parameters. With this approach, optimum results such as cost savings, payback period, and technology investments can be plotted versus different unit-install costs. A breakeven point can be identified through this plot, depending on how the breakeven point is defined. Apart from the breakeven point, the approach can also identify which aspect of the technology must be improved to meet thresholds for competitiveness.

2.7 SR Cost Estimates—First-of-a-Kind and *nth*-of-a-Kind

In addition to the various cost components discussed in previous subsections, there is a need for additional features to represent comprehensively those aspects of SR technologies that are still in the early stages of development. These features encompass cost uncertainties, incentives for these emerging technologies, and the challenges related to the supply chain of fuel and components. Because no SR technologies have yet been commercially released, it is crucial to possess modeling capabilities that can accurately depict the economic and resilience sensitivities associated with the new opportunities and challenges presented by these technologies. FOAK and NOAK cost estimates are considered in the Xendee model to reflect changes in SR cost during the maturation period.

FOAK plants refer to the initial commercial plant constructed for a specific design type, taking into account estimated equipment, materials, and labor productivity [18]. While the experiences and lessons learned from existing large nuclear fleets will be informative, FOAK plants will face unique challenges in terms of cost burdens and extended timelines due to research, experimentation, design certifications, and approval processes [19]. By analyzing FOAK plants, valuable insights can be gained regarding potential cost overruns and extended timelines, enabling more-comprehensive cost estimates for future deployments [20]. FOAK plants also provide crucial insights into operational issues that may arise when utilizing SRs in microgrids and various non-power applications. These operational scenarios differ significantly from the power production for the large, stable grids in which nuclear plants have the most experience operating.

FOAK projects often encounter unforeseen problems during construction, which may necessitate the use of different components or significant design changes, resulting in more-expensive and fundamentally different configurations [18]. Drawing from the current experience with nuclear plants, FOAK plants tend to be 15–55% more expensive than subsequent plants [21]. The lack of infrastructure for timely manufacture of plant and fuel components, as well as the absence of flexible nuclear-waste and spent-fuel management systems, means that the initial deployments of SRs will also face significant challenges related to the supply chain and resilience.

The exact definition of NOAK is not widely standardized. It refers to a stage in which the number of deployments has reached a point at which the learning experience has minimal impact on reducing plant cost. By the time NOAK plants are developed, the potential cost and operational opportunities and challenges associated with plant design, installation, and markets have already been addressed. The investment- and operation-cost estimates for NOAK plants are reliable. The cost reduction of NOAK plants is influenced by various factors, including factory fabrication and learning.

The smaller size and modularity of SRs present a unique opportunity for factory fabrication. Standardized modular units can be manufactured in a factory setting, transported to a site, and assembled rapidly, resulting in decreased construction costs and increased learning. Factory production optimizes unit costs through techniques such as identifying areas of improvement, collecting and analyzing data and performance metrics, and implementing changes to enhance productivity, efficiency, quality, and overall performance. Advanced technologies such as robotics, automation, and artificial intelligence can be employed in factory settings to improve precision, reduce human error, and enhance production.

Learning is a well-understood and proven phenomenon in the manufacturing industry. Considering that factory-produced units and components are used to build an SR plant, the learning process would resemble that of Navy shipbuilding programs, which have reported an average learning rate of 10% [22]. This means that the estimated cost of the reactor module can be reasonably reduced by 10% for every doubling of the number of modules. O&M can also benefit from learning, leading to cost-efficiency improvements.

Sensitivity analysis indicates that advanced nuclear plants can attain cost competitiveness with combined-cycle natural-gas plants as the technology matures [23]. However, the transition from FOAK to NOAK is a challenging step. Once the technology is tested, evaluated, and approved in initial deployments, a significant investment effort is required to establish production infrastructure and develop a supply chain to meet the demand for plant and fuel components. While government support and incentives are vital for this stage, market acceptance plays a crucial role in attracting investors to this new venture. Moreover, the level of market penetration depends heavily on the technology's ability to continuously improve cost and performance, as well as demonstrate the necessary safety, security, and reliability standards to gain social acceptance.

For SR technologies, microgrid markets and cost targets need to be defined based on the electricity prices they can offer during the technology's maturation period from FOAK to NOAK. The first few deployments are likely to be funded by government entities such as the Department of Energy (DOE) and the Department of Defense (DoD). The DOE conducts research and designs, demonstrates, and evaluates these technologies to ensure a clean, resilient, and sustainable energy future. The DoD considers SRs as one of the candidate generation technologies to power remote military sites and establish resilient mobile generation technology for disaster relief. These applications are typically not driven solely by profitability considerations but are crucial for understanding the technical feasibility and economic viability of the technology.

The Xendee platform incorporates an adaptive multiyear modeling feature that facilitates the technology-maturation analysis of SRs (Figure 2-12). This feature enables users to specify fixed or custom percentage increases or decreases in investment and operation and maintenance (O&M) costs for the technology. This capability enables microgrid investors to make informed decisions based on the progress and maturation of the SR technology.

Figure 2-12. Adaptive multiyear modeling feature in Xendee to represent FOAK and NOAK for SRs.

By leveraging this feature, microgrids can optimize unit-deferral decisions, which involve postponing a portion of the project to take advantage of cost reductions resulting from the learning process. For instance, in a microgrid with increasing demand, it may be economically better to gradually add modular units over time—rather than to deploy all at once—to capitalize on decreasing costs while effectively meeting growing demand. The multiyear modeling feature in Xendee provides the necessary flexibility to analyze and optimize such investment decisions in light of the technology's maturation and associated cost changes.

3. SMALL REACTOR TECHNOLOGIES FOR MICROGRIDS

This section provides a condensed discussion about reactor technologies and factors related to technology readiness and considerations that must be made in deciding which technologies are appropriate for a given application of SRs in microgrids.

3.1 Advanced Nuclear Reactor Technologies: Brief History and Path Forward

The first use of nuclear reactors for electrical generation was with a research reactor known as the Experimental Breeder Reactor I (EBR-I) in the National Reactor Testing Station (INL since 2005) located in Arco, Idaho, with startup on December 20, 1951 [24]. Since that time, reactors technology has advanced from the first pressurized water reactors (PWRs) developed for the US Navy (USS Nautilus, 1955) to become a major source of carbon-free power in the current light-water reactor (LWR) fleet in the US and nuclear power plants (NPPs) around the world. Despite headline grabbing events, NPPs have provided an extraordinary amount of clean energy with a safety record that is second to no other energy technology.

The economics and performance of Generation (Gen) I and II reactors have been established as major generations in the power system in the United States, with low average production costs (less than 2 cents/kWh) and a capacity factor of more than 90% accounting for 18.2% of generation in the US (as of 2023) [25]. The path to economic success of Gen III and III+ reactors has been challenged due to project delays, regulatory uncertainties, and decreases in the cost of variable wind and solar energy. Research and development for advanced nuclear were initiated in the early 2000s, with goals to achieve competitive pricing and reliable energy production while also addressing safety, waste management, proliferation, and public concerns [26]. Based on expert technical meetings, technology development and deployment roadmaps were created with four overarching goals: sustainability, economics, safety, and security. Six different reactor technologies were identified: the gas-cooled fast reactor, lead-cooled fast reactor, molten-salt reactor, sodium-cooled fast reactor, supercritical water-cooled reactor, and very-high-temperature reactor. Many of these advanced concepts are proposed in a wide range of sizes to support a variety of applications, ranging from replacing aging fossil-fuel plants in large grids to supporting industrial needs, as well as supplying clean electricity and heat to smaller end users in microgrids.

3.2 Small Reactor Technologies

Some advanced-reactor technology designs have the potential to have a smaller physical footprint to provide greater flexibility in terms of siting, modularity, and advanced safety features that will appeal to military, industrial, and community-resilience microgrids. The SRs that are sized below 100 MWe to cover this range of microgrid applications are anticipated to be of most interest.

It is important to understand the characteristics of SR technologies to choose the one best suited to a particular microgrid application. SRs are being developed along various reactor-technology lines, including water-cooled, high temperature gas-cooled, liquid metal-cooled fast-neutron spectrum, molten salt, and heat-pipe reactors (primarily in the microreactor range) [5], [27]. This report aims to examine the technical characteristics of SRs being developed along these lines to pave the path forward for technoeconomic modeling and database development for various microgrid applications.

The types of SR are described below, with consideration of their technology, cost and operational characteristics, and the advantages that they bring to different microgrid applications. The technologies are distinguished primarily by the coolant used to transport heat from the reactor core to components that make use of the heat directly or convert it to electricity. Other distinguishing characteristics include fuel and integration of heat extraction and storage in the design. Electricity power-conversion components and modularity are other distinguishing factors. The following section summarize the advance-reactor designs distinguished by cooling mechanism. Supplementary material presenting a list of the most-promising SR technologies suitable for microgrid applications, as reported by IAEA, is provided in Appendix A-2.

3.2.1 Water Cooled

Water-cooled SRs leverage decades of industry experience with traditional LWRs. Most emerging water-cooled SRs are integral pressurized water reactors (iPWRs), which use integral designs to confine the primary coolant subsystems (reactor core, generators, pumps) within a single pressurized vessel [5], [28]. This reduces the containment size and eliminates the need for large piping structures, significantly reducing the chances of loss-of-coolant accidents. Additionally, these reactors use natural circulation of primary coolant, in contrast to the forced circulation of conventional designs, which reduces the safety system's dependence on electrical power. This means that the reactor core can cool down and shed decay heat during abrupt shutdowns, even without electrical power supply. The temperature output of water-cooled reactors ranges from 250–300°C, which is suitable for direct low-temperature industrial applications of heat. Electricity is generated by steam turbines that use a Rankine cycle. Some water-cooled designs are developed for marine environments and can be placed as floating power units or submerged underwater.[b]

3.2.2 Liquid-Metal Cooled

Liquid-metal-cooled reactors use molten metal as a primary coolant. The use of metal coolant provides an advantage of high heat-removal capacity at high temperature and lower pressure [9]. Traditionally, older metal-cooled designs were available in thermal-, intermediate-, and fast-neutron spectra. Metallic fuels are preferred to avoid the neutron-moderating effect. A fast-neutron reactor with

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[b] The KLT-40S, a 35 MWe floating SR unit, is the first to be deployed in the water-cooled category. It started commercial operation in Pevek, Russian Federation, in May 2020. Water-cooled SRs are likely to be the first to be deployed commercially in the U.S. NuScale's SMR is leading the way with significant government support. Each NuScale unit is sized at 77 MWe.

metallic fuel has good neutron economy and breeding capability, enabling reactors to operate for several decades without refueling, which is ideal for microgrids developed for remote locations.

Typically, metals such as sodium, potassium, lead, and lead-bismuth eutectic alloys are considered for coolants [29]. Sodium's ideal thermal properties, operating between 400 and 600°C, also have the capability of passive heat circulation and load following, with negative reactivity feedback[c]. Because these eutectics are generally non-corrosive, the designs have enduring integrity and need less maintenance. Molten sodium, however, has some challenges due to leakage and interaction with carbon and some metallic structures, causing corrosion. Containment designs are also complicated by sodium's energetic chemical reaction with air and water. Potassium coolant, on the other hand, has a negligible void coefficient due to a small neutron-capture cross-section. It has boiling point of 759°C, which is comparable to that of sodium (883°C). However, potassium coolant produces hazardous radioactive isotopes. Lead, on the other hand, is relatively non-reactive with air and water, which simplifies the containment design. Similarly, due to the high boiling point of lead (1750°C), the voiding due to evaporation is also minimal compared to sodium coolants. During accidents, lead solidifies immediately, limiting the accidental release of radionuclide. Some lead-cooled reactors have inherent safety features by maintaining the reactivity gradient less than the delayed neutron fraction, meaning the reactor cannot become critical with prompt neutron alone. Despite being an excellent coolant, lead still has the disadvantage of being heavy, opaque, and corrosive at high temperatures (i.e., 500°C and above). Another disadvantage of lead is its high melting point (327.5°C), which makes it difficult to maintain in a liquid state while reactor is shut down. The lead-bismuth eutectic (LBE) alloy, which consists of 44.5% lead and 55% bismuth, has reduced this melting point while it preserves the high boiling point characteristics of lead (1670°C). Additionally, LBE has better thermal conductivity, low thermal expansion, low neutron absorption, and low reactivity with water. The drawback, however, is that LBE produces the toxic product polonium, which has affinity with lead to form a Pb-Po bond that, if leaked, can interact with hydrogen and air, forming highly volatile products. LBE is also corrosive to steel, but this can be reduced by adding an oxide structural layer.[d]

3.2.3 Heat-Pipe Liquid-Metal Cooled

A subset of liquid-metal-cooled reactors uses heat pipes to move heat out of the core. The liquid absorbs heat from the fuel rods and vaporizes. The vapor then travels to a cooler region of the reactor, where it condenses and releases its latent heat, which is then transferred to a heat exchanger for use in electricity generation or direct-process heat extraction. Safety is enhanced due to passive circulation; heat pipes do not need external pumping. Heat-pipe reactors are typically very small and simplified designs significantly reducing the maintenance requirements [30],[31]. Another advantage of heat-pipe reactors is that they can be designed to operate at high temperatures, which increases their efficiency and makes them useful for process-heat applications. Heat-pipe reactors typically use metallic fuels in a fast-neutron spectrum. Molten sodium (Na), potassium (K), or NaK are used as working fluids at high temperatures around the boiling point [31]. Potassium heat pipes operate around 760°C; sodium at around 880°C. Depending on the operating temperature, the structural materials for heat pipes must be evaluated. Heat-

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[c] Fuel and coolant temperatures exhibit a robust negative feedback effect on reactivity. This property can be leveraged to improve reactor power-control capability.

[d] Alloys of uranium fuels and zirconium are preferred due to their high melting temperatures and better chemical and mechanical stability. EBR-I, the first nuclear reactor developed for electricity production, was a metal-cooled reactor using NaK coolant. Toshiba's 4S (Super-Safe, Small & Simple) is the fast reactor developed by Toshiba Corporation and the Central Research Institute of Electrical Power Industry, Japan. It employs sodium coolant. Westinghouse's eVinci and Oklo's Aurora microreactors both use sodium coolant in the sealed heat pipe—the former is an intermediate-spectrum while the latter is a fast-spectrum reactor. SEALER-55 is a lead-cooled SR developed by LeadCold while MicroURANUS uses LBE for coolant.

pipe reactors are typically very small, with simplified designs that significantly reduce maintenance requirements.[e]

3.2.4 High-Temperature Gas Cooled

The high-temperature gas-cooled reactor (HTGR) uses high-temperature capabilities offered by CO_2 or helium gas to enable highly efficient reactor designs at low pressure. HTGR's high-temperature output enables high-temperature process-heat applications. The typical core-outlet temperature ranges from 750 to 950°C. Helium coolant is preferred because it is inert. HTGRs have strongly negative temperature reactivity due to the high temperature of fuel and moderator. HTGRs are inherently safer and have very low risk of meltdown. They use graphite blocks and TRi-structural ISOtropic (TRISO) particle fuel in the core to withstand high temperatures [9]. In addition to pebble-bed HTGR designs, TRISO particle fuel can be embedded into rod-shaped or prismatic graphite matrices to provide uniform neutron flux and temperature distributions, allowing better control over the control-rod shutoffs and proliferation resistance. In HTGR designs, however, the fuel modules are replaced more frequently (approximately every 2 years) than in other reactor types.[f] The integration of fuel structure with coolant or nuclear absorbent, non-nuclear components will create additional radioactive waste in the main fuel cycle.

3.2.5 Molten-Salt Cooled

Molten-salt-cooled reactors (MSRs) use molten salt as coolant.[g] These reactors can use either solid or liquid fuels mixed with molten-salt coolant [9]. MSRs operate at close to atmospheric pressure, reducing the need for large, expensive pressurized reactor vessels. They operate at very high temperatures (650–800°C) providing better efficiency for electricity generation and different high-grade process-heat opportunities. Due to their high temperature, they have strongly negative reactivity coefficient of temperature, adding to their inherent safety.

Liquid fuel has the advantage fuel addition and removal of spent-fuel product while continuing operation. Liquid fuels can also be drained from the core during emergency conditions, which is one of the reactor type's inherent safety features. However, the absence of fuel cladding takes away a structural and radiological defense of reactors with solid fuels. Further, chemistry must be monitored and controlled carefully to avoid corrosion in structures.

TRISO particle fuels can also be used in MSRs. Particle-fueled MSRs typically use graphite as moderator to absorb neutrons and control the nuclear-fission chain reaction. Graphite moderator, however, can expand or shrink when exposed to high temperatures and irradiation, creating a structural gap between fuel blocks. Graphite, when heated, can release water moisture, causing fuel-kernel failure

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[e] The Mobile-Very-small reactor for Local Utility in X-mark (MoveluX) is a 10 MWt heat-pipe reactor design developed by Toshiba, targeted for electricity, hydrogen, and high-temperature heat and suitable for off-grid electricity applications. It uses molten-sodium coolant and calcium hydride as moderator and hexagonal silicide (U_3Si_2) fuel assembly. eVinci is another heat-pipe reactor being developed by Westinghouse, leveraging the MegaPower technology developed by Los Alamos National Laboratory (LANL). It plans is to use TRISO particle fuel.

[f] Xe-100 is a pebble bed high-temperature gas-cooled reactor being developed by X-energy featuring a continuous refueling system providing a final average burnup rate of 165, 000 MWd/tHM. AHTR-100 is a 50 MWe pebble-bed HTGR developed by ESKOM. U-battery (4 MWe) by Urenco, and Holos-Quad (10 MWe) by HolosGen are some of the reactor concepts with TRISO fuel embedded in a graphite structure. HolosGen is based on the General Electric's nuclear turbojet concept from 1960s.

[g] MSRs were first experimented with in the 1950s for aircraft propulsion with molten actinide fluoride fuels. During the 1960s and 1970s, experiments were done to understand handling of uranium- and thorium-based fluoride fuels and the feasibility of use in reactors for power generation focusing on corrosion issues, fission-product containment, and radiation-exposure assessments. Some MSR technologies at microgrid scale include Mk1 PB-FHR, a 100 MWe pebble-bed reactor with TRISO particle and graphite core, using Li_2BeF_4 molten-salt coolant, and Waste Burner by Copenhagen Atomics, which is a 20 MWe that uses molten-salt fuel with LiF-ThF_4. TMSR-LF1 is a 2 MWt liquid-fueled thorium-based MSR developed by China.

by hydrolysis. These reactors are also typically larger than other reactor technologies at the same power level, increasing capital costs.

3.3 Reactor Fuel

Nuclear fuels contain heavy actinide elements capable of undergoing fission chain reaction. In fission chain reactions, an unstable nucleus is hit with a free neutron, splitting it into smaller, daughter nuclei while in the process releasing more neutrons. A vast amount of heat energy is released during this process; this is captured from reactor core using coolant and supplied to a variety of energy applications.

Most SR technologies propose refueling intervals that are longer than traditional LWRs. Instead of using the rare U-235 isotope, new fuels proposed include reprocessed uranium, metal-oxide (MOX), transuranic (TRU) fuels and breeding more common thorium (Th-232) and U-238 into fissile U-233 and plutonium (Pu-239) using fast-reactor concepts [9].

3.3.1 Fuel-Cycle and Supply-Chain Challenges

Figure 3-1 illustrates the fuel cycle from the mining of uranium ore through the fabrication of fuel into forms usable in SRs, including the possibilities for recycling spent fuel and final disposition of fuel products that are not useful to the safe production of nuclear energy. The uranium mineral is passed through different stages to produce fuel that can be used in nuclear reactors; this is the front-end fuel cycle. It includes four major stages: milling, conversion, enrichment, and fabrication. The ore is smelted and converted into either pure uranium dioxide (UO_2) or uranium hexafluoride (UF_6). Non-heavy-water reactors use UF_6, which is typically enriched into 3–5% U-235. Enrichment separates the U-235 isotope from UF_6 to form either low-enriched uranium (LEU) fuels, containing U-235 at levels below 5%, high-assay low-enriched uranium (HALEU), containing U-235 at levels between 5 and 20%, or highly enriched uranium (HEU) fuels, containing U-235 at levels greater than 20%. Today's commercial LWRs use LEU. Most commercial advanced SRs designs will use HALEU and LEU. HALEU can potentially improve reactor performance, reduce waste production, and increase the lifespan of nuclear fuel. However, the production of HALEU requires advanced enrichment technology and is more expensive than producing LEU. The US is developing a supply chain for HALEU to avoid dependency on Russian-produced fuel.

Fabrication—in which UF_6 is converted into UO_2 and processed into pellet form—is the final process. These pellets are stacked into tubes of corrosion-resistant metal alloy (e.g., zirconium) to form fuel rods. These fuel rods are grouped and loaded into reactor core as fuel assemblies.

The back end of the fuel cycle involves removing spent fuel from the reactor vessel, interim storage, and final disposal. The spent fuels can either be reprocessed or be directly disposed. Reprocessing allows the recycling of unused uranium and plutonium in the form of reprocessed uranium oxide or mixed-oxide fuel. Different subsidiary facilities are needed for a reprocessing plant, including a recycled-fuel fabrication unit, a vitrification unit, a waste-conditioning unit, with a final repository for high-level waste. On the other hand, direct disposal requires an interim storage facility, an encapsulation facility to prepare waste-fuel bundles for disposal, and a deep geological repository (DGR) for final disposal. Reprocessing plants use large amounts of chemicals. Reprocessing is an expensive option and is not economical in the current state unless the cost of producing new fuel is exceedingly high.

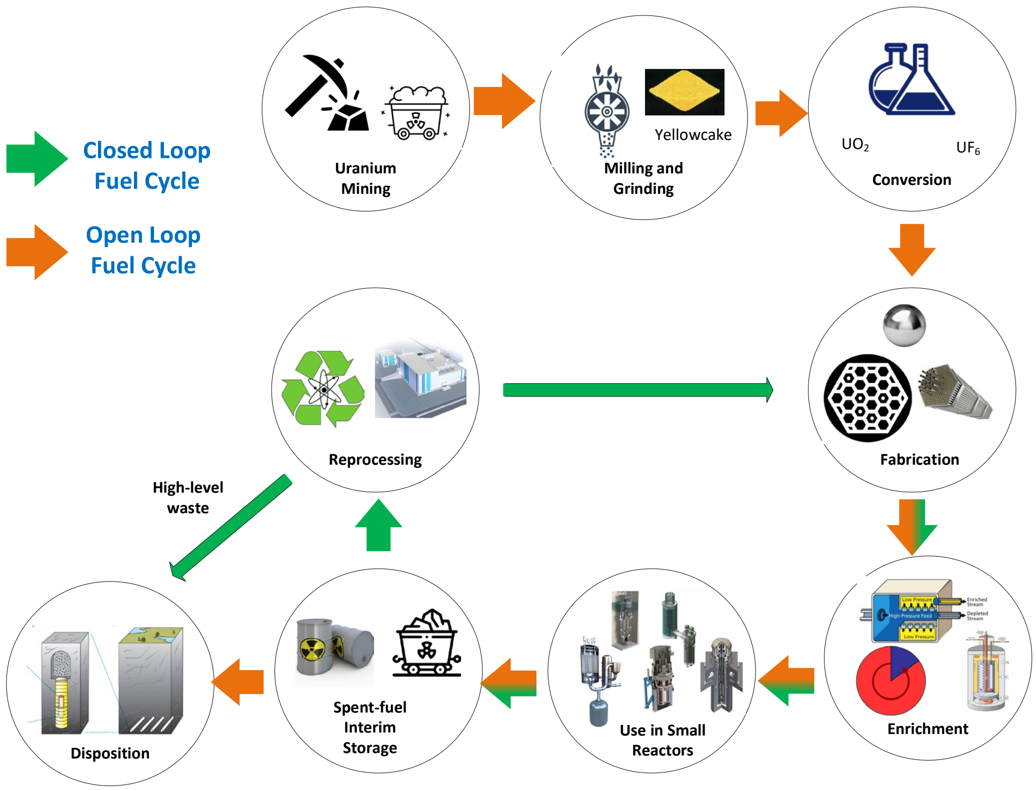

Figure 3-1. Nuclear fuel front-end and back-end life cycle.

3.3.2 Fuel Types and Refueling Requirements

Most water-cooled SR concepts use existing fuel designs and a fuel-cycle approach based on U-235. Enrichment is typically below 5%, with a burnup rate as high as 160 GWd/tHM and refueling interval of 2–10 years [5]. The refueling outage is typically between 18 and 36 days. Refueling for water-cooled SRs will typically be done in batches, with three-batch refueling where one-third of the core is replaced in each refueling cycle to improve burnup. The marine-based water-cooled SRs, however, are designed with higher enrichment (up to 20%) to enable longer fueling intervals while satisfying proliferation limits. Some SR concepts consider online refueling, reducing the outage time needed for refueling. Online refueling improves fuel use and refueling costs. This, however, requires complicated mechanisms. There are some existing technologies, such as the Canada Deuterium Uranium (CANDU) Reactor, that have online-refueling capability.

Liquid metal-cooled reactors have higher enrichment of U-235 and longer refueling cycles of up to 30 years. Most concepts use the closed nuclear fuel cycle to efficiently use natural uranium with breeding concepts starting with U-238 to create plutonium as a basic fuel. They can also use TRU elements from LWR spent fuel.

HTGR concepts use accident-tolerant fuel designs. Most of them are based on pebble-bed or prismatic-core designs with multilayer coated TRISO particle fuels or hexagonal assemblies using uranium carbide or UO_2 fuels [5], [31]. The enrichment level is typically between 8.5 and 19.75% to ensure higher burnup rates (up to 165 GWd/tHM). Pebble-bed concepts enable online refueling; by contrast, prismatic concepts offer longer periods between refueling or no refueling at all. HTGRs can use both open and closed fuel cycles. But most HTGRs will start with an open-cycle option. Pebble-bed fuels can be recycled if the fuel has not reached the desired burnups, which significantly improves the burnup and sustainability of fuels. In the closed fuel cycle, spent fuel spheres are dismantled and sent to reprocessing facilities. HTGRs that use coated-particle fuels in graphite prisms also use batch refueling.

The pebble-bed and molten-salt SRs can be refueled online and are also capable of removing fission products while online.

TRISO fuels are also being considered for molten-salt reactor concepts. TRISO fuel has some limitations in terms of packing fraction [31]. The current limit for TRISO packing fraction is approximately 40% before the particles begin to experience damage during compacting. The reactor core structure housing TRISO fuel is likely to be made of graphite blocks. Methods for manufacturing nuclear-grade graphite will need to be defined.

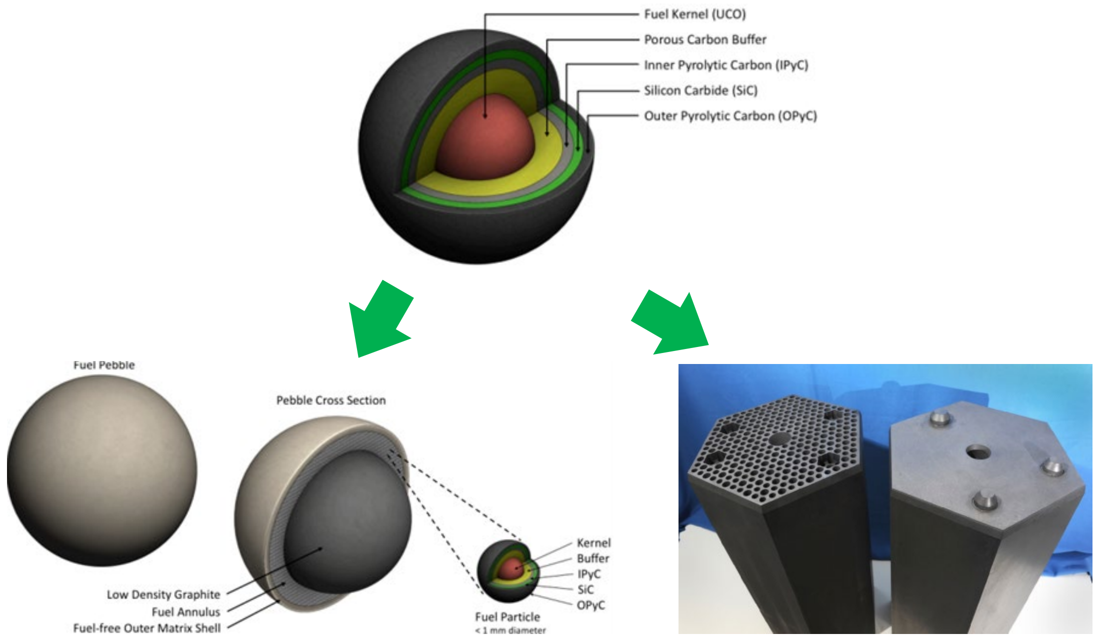

Figure 3-2. TRISO fuel structure used in spherical fuel pebble and prismatic graphite blocks. [32]

The liquid-fuel structure of MSRs means the fuel is not prone to structural failure or mechanical damage. Some of the concepts include online refueling by adding fuel into molten-salt coolant. Typically, a very large refueling time, up to 15 years, is targeted. The enrichment level varies between 5 and 19.9%. Thorium-salt fuels are used, which are bred to U-233.

LANL-developed heat-pipe-cooled reactors use fuel pellets in a monolithic core structure [30]. Some of the potential designs include a monolithic block of fuel surrounded by a reflector or fuel pins and heat pipes immersed in a liquid-metal bath. TRISO encapsulated fuel is one of the options that can be used in reactors such as Westinghouse's eVinci. MoveluX uses a uranium silicide fuel that has high thermal conductivity and a high melting point.

Another approach taken by some SR technologies is breeding. Breeding involves converting depleted uranium, thorium, and waste actinides to produce fissionable products. This approach to fuel is used by molten-salt or metal-cooled reactors in the fast-neutron spectrum.

3.3.3 Waste Management and Disposal

It is necessary to ensure infrastructures are ready for spent-fuel and radioactive-waste management alongside the technologies. New technologies and fuel-cycle approaches lead to new types of radioactive waste that need to be handled in a manner appropriate to each. Therefore, it is necessary to incorporate the spent-fuel management approaches from an early conceptual design stage. The key question is how the new upcoming technologies can ensure spent-nuclear-fuel and radioactive-waste management while keeping the cost minimal with proven technologies, especially for the designs which may lead to new forms of waste for which the disposition path is not already extant. Refueling interval is another consideration to be considered. The newer designs, with longer refueling cycles of 3–30 years, would potentially reduce the task of nuclear-waste management while requiring strategies other than the traditional approach [5]. Similarly, it is necessary to understand how the design, operation, and eventual decommissioning of SR technology can influence the type of waste produced by the technologies.

The national policy of a country is also important in nuclear-waste management. Especially for the nations with no prior nuclear experience, it is important to address the questions surrounding responsibilities and ensure funding mechanisms for spent-fuel and radioactive-waste management for the SR developers.

Current solutions exist in the form of reprocessing and recycling of spent fuel and the disposition of high-level waste in DGRs while advanced approaches, such as partitioning and transmutation, can further reduce the impact of nuclear waste. Advances are also being made in dry-storage technologies. The experience built over the years for research and power reactors and the advancement in computer models provide a valuable resource for simulation and prediction of new waste forms with newer technologies.

Most upcoming advanced-reactor technologies propose to use existing infrastructure and adapt them for new waste streams [33]. Water-cooled SRs adopt concepts like that of existing water-cooled reactors for spent-fuel management. More emphasis is given to volume reduction and conditioning. In iPWR designs, the separation of the reactor pressure vessel (RPV) from core with material and components in between reduces the impact of fast neutrons on the RPV material, lowering the challenges of maintenance and decommissioning. For some of the marine-based floating-reactor concepts, the spent fuel and nuclear waste produced on board will be taken back to supplier countries for reprocessing and disposal. For interim storage, typically, internal recycling systems are designed to reduce radioactive waste. In some of the floating concepts (e.g., ACPR50S) liquid, solid, and gaseous radwaste systems are separately designed to minimize the radioactivity and amount of waste for interim storage [5].

Due to their high burnup rate, HTGRs produce significantly lower high-level waste (about 40% less) than typical LWRs. The amount of plutonium is just one-quarter that of typical LWR cycle [5]. The silicon carbide coating layer in TRISO fuel provides multibarrier containment with significantly lower source term. It is also preferable to separate coated particles from the graphite matrix in prismatic fuels because they need significantly more space if dispositioned without volume reduction. This is because the uranium in each pebble sphere is only 1%. HTGRs typically have dedicated on-site waste handling systems for solid and liquid wastes.

One primary driving factor behind the fast-neutron liquid-metal-cooled reactor concepts is their capability to generate significantly reduced quantities of high-level waste. Some design aspects of metal-cooled concept also contribute to the reduction of nuclear waste. A potential issue of the fuel cycle of MSRs is the management of spent molten salts. Gaseous products are actively removed during operation and stored onsite to decay. The complex mixture of fuel and molten salt will be difficult to manage as a high-level waste. The potential reprocessing routes require pyroprocessing technologies, and there is no commercial pyro-reprocessing plant in operation so far. In reprocessing facilities, actinides can be separated from salt, and salt will be stored to cool-down.

3.3.4 Proliferation Resistance

The potential use of SRs in microgrids presents challenges related to nuclear proliferation due to the distributed and decentralized nature of these energy systems. Conventional NPPs are designed with stringent safeguards and security measures to prevent unauthorized access to nuclear materials and to ensure the safe handling and disposal of radioactive waste. However, implementing similar levels of safeguards and security for a large number of microgrid systems at small-scale with limited financial resources and technical expertise can be more complex and challenging.

Advanced nuclear technologies offer several advantages in terms of proliferation resistance. Due to high fuel burnup in HTGRs and metal-cooled fast reactors, they produce lower Pu-239 assay, enhancing their proliferation-resistance characteristics. In addition, their longer core-refueling periods make it more difficult to isolate fuel from the reactor, which would otherwise potentially enable unauthorized access.

Onsite refueling increases the possibility of fuel tampering for weapon purposes, leading to a proliferation risk. Battery-type reactor concepts can operate throughout the reactor lifetime without refueling. To enable extended operation, these concepts require an initial loading of large amounts of fissile material, often with high enrichment levels [9]. Battery-type reactors are especially suitable for remote locations where refueling is not feasible. Notable examples of battery-type concepts include Elena, Unitherm, ABV-6M, eVinci, and MMR, with the 4S being a fast reactor employing a battery concept.

Similarly, the TRISO spherical fuel structure and its use in embedded prismatic structures offer inherent proliferation resistance. These coating layers of carbon and ceramic materials act as barriers to contain the radioactive materials, provide redundancy, and increase the difficulty of accessing and extracting the fissile material for illicit purposes. Similarly, the fuel dispersion in embedded graphite matrix in prismatic fuel makes it challenging to access and remove fissile material from the fuel elements without sophisticated equipment and techniques.

The use of TRU fuel has also shown promise in enhancing proliferation resistance. The plutonium-content reduction, high radiation-dose rate, and heat-generation rate make it difficult to handle these materials at the extraction, transportation, and weaponization stages [34]. This indicates the possibility of cost-effective management of spent-fuel safeguards.

Proliferation resistance can be improved by employing an underground siting approach for nuclear reactors. Underground siting provides natural physical protection against external threats, such as sabotage or terrorist attacks. Advanced containment structures and tamper-evident seals can be integrated into the facility design to enhance the security and accountability of nuclear materials.

It is essential to develop specific guidelines and regulations tailored to the integration of nuclear power in microgrids. These guidelines should emphasize the importance of robust safeguards, security, and monitoring measures, even in small-scale nuclear systems. International cooperation and information-sharing can also play a significant role in providing technical support, sharing best practices, and facilitating the adoption of standardized non-proliferation measures across microgrid deployments involving nuclear power.

3.4 Power-Conversion Systems

The power-conversion system, often referred to as the balance of plant, is an important part of a nuclear power plant. It can be roughly separated into heat engines and generator. The heat engine converts heat produced in the reactor through fission traction into mechanical work. This mechanical power is used to run generators to produce electricity. The mechanical work produced by heat engines is proportional to the temperature difference between their hot and cold sides. Irrespective of the type of engine, efficiency is higher at higher temperature difference. The theoretical maximum-efficiency heat engines are obtained as $\eta = \frac{T_{hot}-T_{cold}}{T_{hot}}$ [35]. The efficiency can be increased by both increasing the temperature of the hot side and lowering the temperature of the cold side of the heat engine. This is the reason why the exhaust of the turbines of NPPs are maintained at significantly lower temperatures with the help of cooling towers to improve conversion performance.

Heat engines are of different types, depending on the type of fluid involved and the thermodynamic processes. Some of the major thermodynamic processes applicable to SRs are discussed in the following subsections.

3.4.1 The Rankine Cycle

The Rankine cycle is the most-common type of thermodynamic cycle for electricity production in the world today [35]. The working fluid receives heat produced from nuclear fission and runs through a steam generator where it transforms from a liquid into a gaseous phase. The gas then travels to a turbine where it expands, releasing the heat stored into mechanical work. Water is usually chosen as working fluid for its simple chemistry, relative abundance, low cost, and thermodynamic properties. The Rankine cycle that uses water as working fluid is called a "steam engine."

Figure 3-3 shows a detailed physical layout of a Rankine cycle. While expanding in turbine, the steam loses the heat and becomes a two-phase mixture. The efficiency of the steam turbine is influenced by water-droplets formed during expansion. The water droplets hitting the turbine blades can cause pitting and erosion, resulting in the turbine's reduced efficiency and lifespan. Therefore, steam is usually superheated before its supply to the turbine. In practical applications, the Rankine cycle often includes multiple turbines operating at different pressure levels. A reheater is usually placed between turbine stages to extract a portion of high-temperature steam to reheat the steam before sending it to the next turbine stage to reduce moisture content. In some setups, moisture separators are also included between turbine stages.

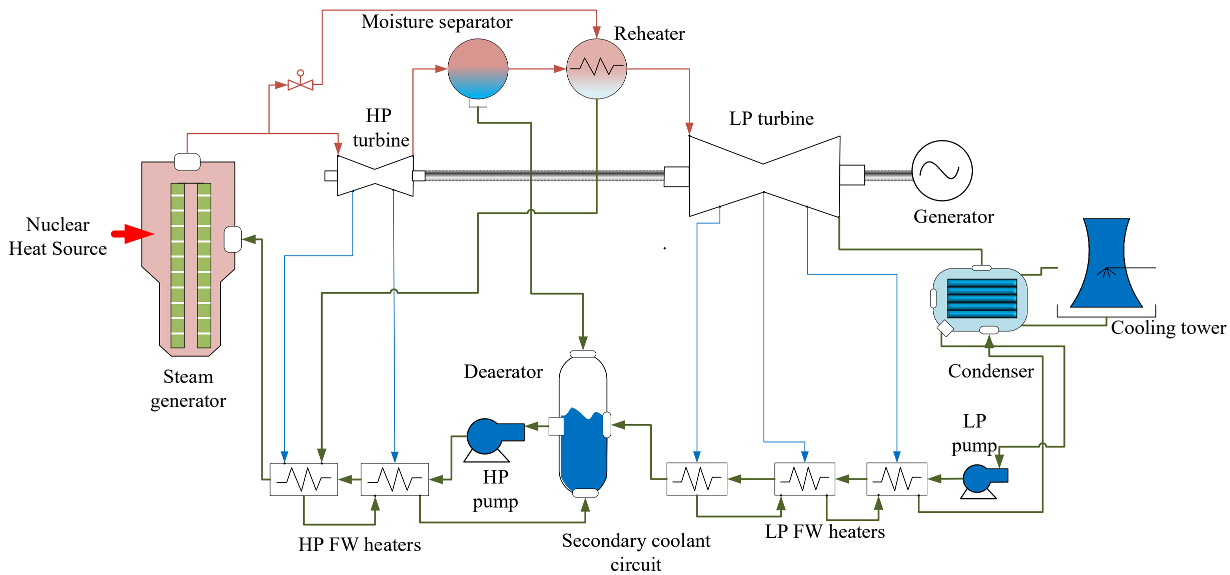

Figure 3-3. Detailed physical layout of the Rankine cycle.

The exhaust from the last-stage turbine is sent to a condenser, which condenses the fluid into a subcooled liquid. Prior to its being sent to the steam generator, the feedwaters are usually preheated using feedwater heaters to improve the efficiency of the thermodynamic cycle. Bleed steams from turbines are used to preheat feedwater using closed-loop heat exchangers in which the heating fluid and heated fluid do not mix. The preheating usually happens in stages: one after the low-pressure feed pump and another after the high-pressure feed pump.

The Rankine cycle is typically suited for low-to-medium temperatures and high pressures. Temperature can depend on the specific application, but typically range between 200 and 600°C. The pressure can go as high as 50 bar. The Rankine cycle is ideally suited for reactor types with a lower operating temperature of primary coolant, as is the case with water-cooled reactors.

The O&M of steam turbines involve specific procedures to ensure optimal performance and longevity. During startup, steam bypass lines and turning gears are employed to gradually warm the turbine, minimizing uneven expansion. Rotor imbalance is a potential issue, so turbines are carefully balanced and operated with high-temperature steam to prevent blade damage from impingement and erosion. Maintenance requirements are generally straightforward and cost-effective, with operational lifespans often exceeding 50 years. Speed regulation is crucial, and turbines are equipped with governors to prevent over speeding. Power plants operate droop-speed control to maintain stability within the electrical grid, with adjustments made by modifying the governor's settings.

3.4.2 Brayton Cycle

The Brayton cycle describes engines that use gas as their working fluids. A variety of gases are considered for working fluids, including an argon-neon mix, helium, supercritical CO_2, and atmospheric air. The working fluid remain in a gaseous state throughout the cycle. The hot, high-pressure gas is expanded in a turbine to produce rotational energy, which drives a turbogenerator to produce electricity. The pressure across the gas turbine directly influences the efficiency of the cycle [35]. The Brayton cycle can be of two types: the first is open to the atmosphere and uses ambient air while the second is closed, in which a gas is circulated in closed circuits.

The open-loop Brayton cycle is shown in Figure 3-4 (a). The ambient air is compressed in a compressor and passed through gas heater where it receives heat. The hot, high-pressure gas is then expanded in the turbine and released to open atmosphere after expansion. There is typically a heat-recuperation stage to capture the heat from the exhaust of the turbine before it is released to the atmosphere. Heat recuperation is critical to improve the thermal efficiency. The open-loop Brayton cycle requires less equipment than the closed-loop Brayton cycle.

The closed-loop Brayton cycle is shown in Figure 3-4 (b). The cold, low-pressure gas coming out of a gas cooler is supplied to the compressor. The compressed gas is then passed through a gas heater where it receives reactor heat. The compression can be done in multiple stages, with an inter-cooler between to reduce the amount of compression work, leading to more-efficient processes. Similarly, a heat recuperator can be placed at the exhaust of the turbine to preheat the air going to the turbine. Heat recuperation helps reduce the amount of heat needed from the gas heater and the amount of heat rejected in the cooler to improve efficiency.

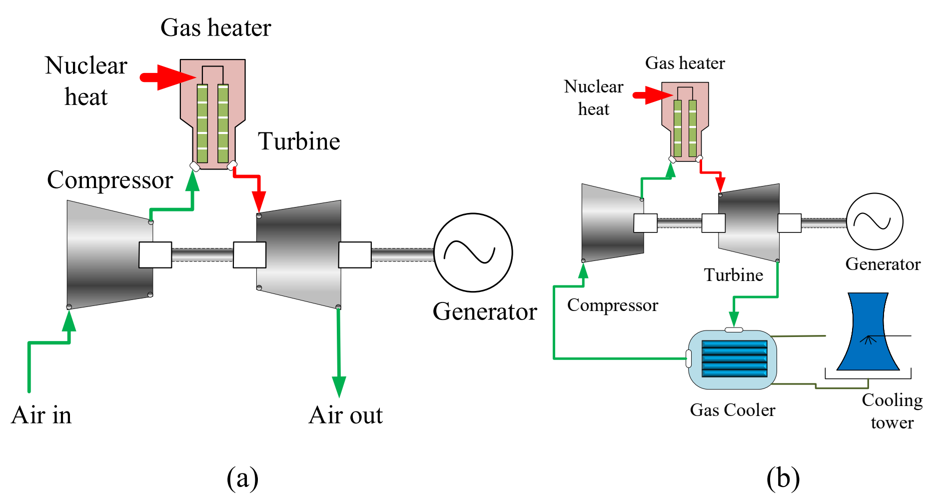

Figure 3-4 (a) Open-loop Brayton cycle, (b) closed-loop Brayton cycle.

The Brayton cycle can operate at both low and high pressure. Higher pressures reduce the equipment size but would require more-expensive designs and materials to withstand thermal and physical stress. The main disadvantage is the much higher rotational speeds and larger volumes of working fluid needed to extract the same amount of power. Brayton cycles typically operate at high temperature and lower pressure than Rankine cycles. The temperature typically is in a range from 500 to 1600°C while pressures are in the range of few bars to tens of bar. Brayton cycles are ideal for reactors with very-high-temperature outputs such as gas-cooled and MSRs.

3.4.3 Combined Cycle

Combined cycle designs integrate both Brayton Rankine cycles to maximize energy efficiency [36]. The common configuration has a gas turbine in the topping cycle and a steam turbine in the bottoming cycle. The combined cycle can achieve efficiency as high as 60%. For high-temperature reactors, the high-temperature heat produced is not very efficient for steam turbines. On the other hand, a significant amount of heat is left in the exhaust of gas turbine if the Brayton cycle is used. Therefore, the nuclear heat is first used in a gas turbine using the Brayton cycle. The heat left in the exhaust of the gas turbine is used to produce steam that, in turn, drives a steam turbine to generate electricity. This combination of high-temperature heat from the nuclear reactor, steam turbine, and gas turbine allows for overall thermal efficiency higher than in standalone steam or gas turbine power plants [37]. Combined-cycle nuclear plants offer an efficient and sustainable means of electricity generation by capitalizing on both the heat from the nuclear reactor and the gas turbine, resulting in enhanced energy use and reduced environmental impact.

3.4.4 Stirling Cycle

The Stirling cycle operates on the principles of cyclic compression and expansion of a working fluid, typically a gas such as helium or hydrogen [38], [39]. The engine consists of a closed-loop system in which the working fluid is cyclically heated and cooled, causing it to expand and contract. This expansion and contraction drive a piston or displacer, converting thermal energy into mechanical work. Stirling engines are typically classified into three distinct types: alpha, beta, and gamma [39]. The alpha type uses two pistons and multiple interconnected cylinders to move the working gas being expanded and compressed based on temperature. The beta and gamma-type engines use a single displacer piston arrangement moving the working gas vertically between hot and cold heat exchangers in the same cylinder. The gamma-type Stirling engine is similar to the beta type but has a power piston mounted on a different cylinder to make it mechanically simpler. The working fluid, however, can flow freely between the cylinders, making them a single body.

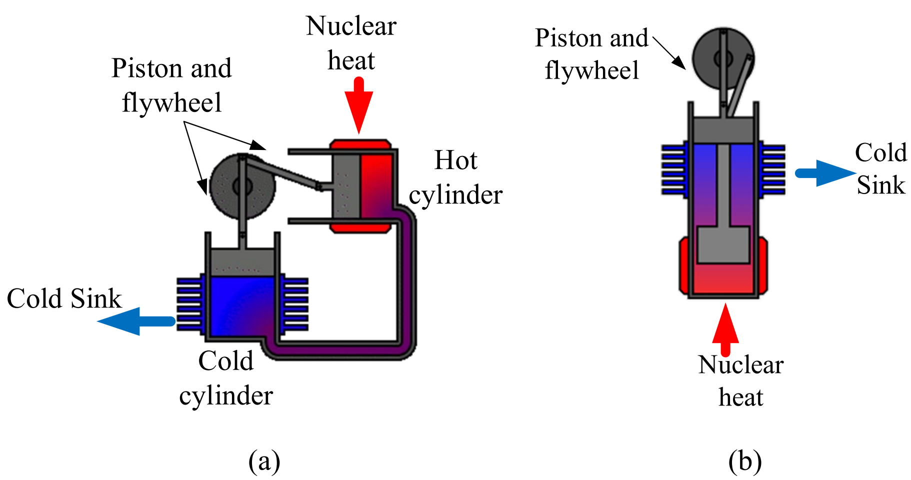

Figure 3-5. Physical layout of a Stirling engine, (a) alpha type, (b) beta type.

Stirling engines can theoretically operate with high thermal efficiency due to their closed-cycle operation and internal constant-volume regeneration. Due to their fewer moving parts and higher thermal efficiency, they are a very attractive option for smaller mobile SR technologies and for space applications. Microreactor Applications Research Validation and Evaluation Project (MARVEL), being developed by Idaho National Laboratory (INL), will use a commercial Stirling engine as its power-conversion system.

3.5 Thermal-Design Configurations

3.5.1 Thermal-Energy Storage

The smaller size of SRs enables the use of TES to decouple the heat-generation and utilization processes for efficient provision of energy balance and flexibility on both the heat and electricity sides. Advanced SRs are typically designed with very-high-temperature output. To be able to store thermal energy efficiently at such high temperatures, new storage media are necessary. Materials with large thermal density, as well as good thermal conductivity, are preferred [40]. Apart from thermal characteristics, the TES material should be capable of withstanding large cyclical thermal loadings without losing structural integrity and should be able to hold thermal properties over longer duration.

TES material can be in a solid, liquid, or gaseous stage. TES can be broadly categorized into sensible, latent, and thermochemical heat storage.

In sensible heat storage, no phase change occurs. The storage materials include hot water, molten-salt, and concrete. For high-temperature heat storage, molten-salt storage materials are ideal candidates [40], [41]. They have very high thermal conductivity and can hold very high temperatures at low pressure. They are stable at operating temperature, remain liquid at atmospheric pressure, and are comparatively lower in price than other high-temperature energy-storage materials. The use of concrete as a TES medium is a relatively new technology that can provide low-cost solutions. The concrete is built with a steel-piping heat-exchange structure through which the heat-transfer fluid flows for heating and cooling purposes [40]. It can be in either single-pipe designs, where the charging and discharging occur using the same pipe structure, or in double-pipe design in which charging and discharging occur through different piping. They can have operating temperatures of up to 600°C and have been demonstrated for up to 1500 thermal cycles without any structural damage.

Alternatively, TES materials may be designed to store heat in a latent form during which a phase change occurs, also known as latent-heat TES. The storage medium, also known as a phase-change material (PCM), can be organic, inorganic, or eutectic salts. The latent heat of fusion is preferred to latent heat of vaporization. Typically, a PCM goes through solid-liquid phase change through melting and solidification. Due to the energy storage in latent heat, they have high heat-storing capacity without affecting the material’s temperature. This means they have higher energy density and therefore require less volume than sensible-heat TES. Due to their lower thermal conductivity and diffusiveness, they are not able to provide quick power ramping.

Thermochemical TES operates on the principle of reversible chemical reactions to store and release thermal energy [42]. It consists of chemically reactive storage materials that undergo endothermic and exothermic reactions to produce and consume heat under a given pressure and temperature condition. The reaction products are separated and mixed during the charging and discharging cycle. Depending upon the type of reactions, the thermochemical TES can provide higher heat storage capacity than sensible heat or latent heat TES. Because the storage and release of the heat is based on controlled chemical reaction, thermochemical TES has tremendous potential to provide long-term seasonal storage capability. It is possible to design lossless long-term storage with large temperature range of greater than 1000 °C [43].

TES could be implemented in several design configurations [40],[44]. Three of these are shown in Figure 3-6. In Configuration A, the TES is positioned between a heat source and its applications, effectively isolating heat generation and consumption. This arrangement offers flexibility on the application side and allows for optimal operation of reactors close to baseload while limiting transients on the primary side. The TES must be appropriately sized to store the energy produced by the heat source while also efficiently storing heat at high temperatures. Implementing such designs can result in higher costs. One example adopting Configuration A is the Micro Modular Reactor (MMR), an HTGR concept developed by the Ultra-Safe Nuclear Corporation (USNC). The MMR incorporates a molten-salt storage loop positioned between the primary reactor vessel and the application sides, serving as an intermediate plant for harnessing and storing heat from the reactor [45]. This stored heat can then be supplied to a variety of heat applications. By using this setup, the application sides can be fully decoupled from the heat source, thereby offering flexibility in sizing and operation.

In Configuration B, TES stores excess heat unused by heat and electricity applications. Both heat and electricity applications have direct channels to the heat source. TES needs to store heat efficiently, at high temperatures like Configuration A, but can be sized smaller based on flexibility needs.

In Configuration C, TES is localized to the heating application side. TES can be sized per the heating-side requirement and stored at a temperature suitable for the heating application. Such a configuration would be cheaper to design but would only provide flexibility on the heating side.

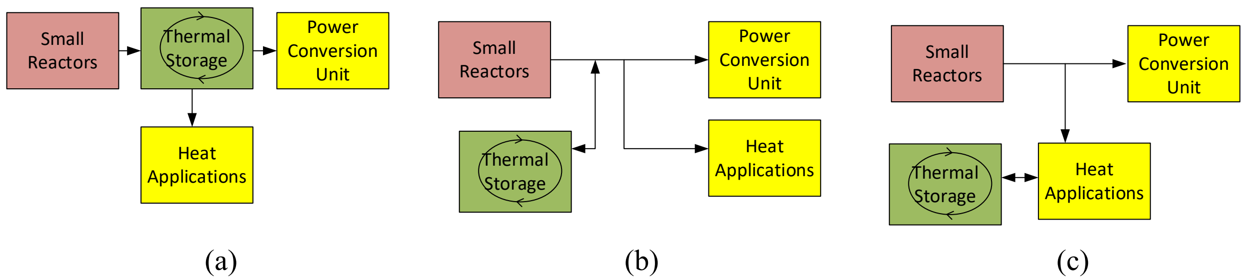

Figure 3-6 Three potential TES design configurations with SRs.

3.5.2 Energy Manifolds

In microgrids, SRs may be used to meet multiple heating applications (Figure 3-7). Different heating processes require different grades of heat. New design approaches are necessary to modify the secondary-coolant network to use nuclear heat for a variety of heating applications. The energy manifold represents the extraction system to use heat from the secondary coolant for applications other than direct expansion in turbines. For high-temperature heating applications, process heat can be directly used. However, high-temperature heat is not efficient for low-temperature heating applications, such as district heating. Unlike CHPs, the heat left at the turbine exhaust of advanced NPPs is at significantly lower temperature, able to be used for low-grade heating applications.

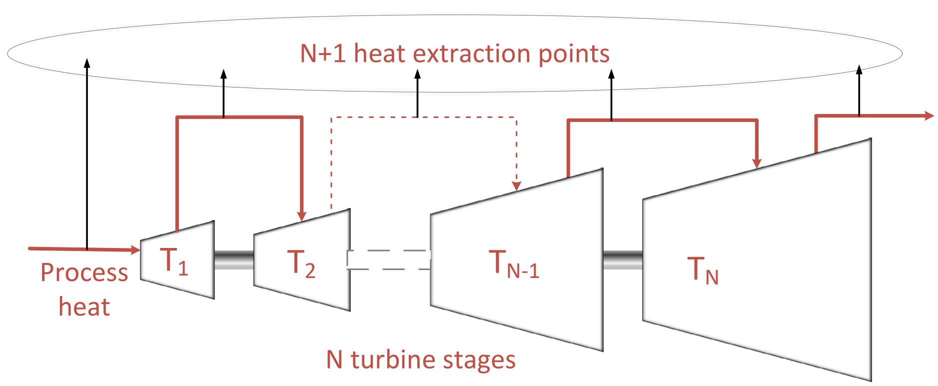

Figure 3-7. Heat extraction from multiple turbine stages.

For non-process-heat applications, heat can be extracted at lower temperatures from an intermediate turbine stage. Figure 2-1 shows a multistage turbine configuration with n turbines and therefore $n + 1$ extraction stages, each with a different temperature grade of heat to select from [46]. Heat extraction from the secondary coolant can add flexibility to the electrical side [47]. For high-temperature heat applications, process heat can be directly extracted whereas, for low-temperature heat applications, the heat can be extracted from between the turbine stages at suitable temperature and pressure.

3.6 Technology-Selection Guidance

Section 3.2 discussed different SR technologies suitable for microgrid applications, delving into their specific characteristics. The SR model presents an opportunity to represent cost and operational characteristics of various SR technologies in an optimization tool, thus enabling technology selection. This section aims to provide initial guidance on technology selection by summarizing the general features of various SR technologies and matching them with the requirements of microgrids. This guidance will prove valuable for both reactor-technology vendors and microgrid planners in comprehending potential configurations and identifying technologies suitable for specific applications. Based on the identified characteristics of SRs and the operational needs of microgrids, the following observations can be considered as commonly accepted.

- SRs with compact size, light weight, and modular construction offer an ideal solution for microgrids operating in remote areas and on islands, where transportation accessibility is limited [5]. Some SRs are modeled as transportable mobile units developed and assembled in a shipyard factory and then delivered ready-to-use to remote sites for plug-and-play energy supply. The potential to place SRs in remote, off-grid communities improves access to clean electricity and heat.
- The smaller size and lower overall capital costs of SRs present an opportunity for a wider range of microgrid applications and a broader spectrum of investors to participate in nuclear-energy markets.
- Modularity allows microgrids with growing demand to add modules incrementally over time, rather than deploying all at once, while capitalizing on the cost reduction due to colocation. This is especially important during the technology-maturation phase (i.e., FOAK to NOAK) when the rate of cost reduction will be very high.
- Factory fabrication and rapid deployment of SRs will reduce construction time significantly. This enables decision makers to swiftly deploy SRs in underserved and disadvantaged communities in need of a reliable clean energy supply.
- The long-lasting nuclear fuel used by SRs is highly beneficial for microgrid communities that have limited access to a central transportation network, such as remote communities and islands. This characteristic allows for years of independent operation without the need for external fuel supplies.
- SRs that are specifically designed with load-following capabilities are well-suited for communities with volatile demand characteristics [12], [15], [48]. This feature proves particularly beneficial for communities seeking to integrate scalable renewable-energy sources, such as wind and solar photovoltaics, alongside SR technologies.
- Certain SR designs offer the ability to operate in autonomous or semi-autonomous modes, which results in a reduced need for skilled operators at the site. This not only lowers O&M costs, but also enables communities with limited skilled-human resources to adopt nuclear technology. This factor plays a crucial role in facilitating the widespread adoption of SRs.
- SRs have the capability to supply clean, high-quality heat in addition to electricity. This is particularly important for microgrid communities with both heat and electricity needs. These microgrids may encompass commercial or industrial facilities with heat-dependent processes. SR designs with high-temperature ratings, such as high-temperature gas-cooled reactors and MSRs, are well-suited for microgrids with substantial industrial heating demands. The availability of high-quality heat from SRs also provides opportunities for residential communities to explore commercial ventures within microgrids. In microgrids situated in cold regions, the heat generated by SRs can be effectively used to fulfill district-heating needs.
- Due to their smaller size and robust safety features, SRs have reduced plant footprints and emergency planning zones (EPZs). This characteristic makes SRs an appealing generation option for microgrids situated in densely populated urban areas and metropolitan hubs, thereby expanding the market

opportunities for SR technologies. The compact nature of SRs allows for their integration in space-limited environments while ensuring the safety and security of the surrounding areas.

- Inherent safety designs and engineering features of SRs are crucial for their widespread deployment in microgrids. Such features not only provide reassurance to end users, helping to overcome social acceptance challenges, but also assist regulators in easing regulatory barriers.
- Integrated design structure, where reactor components are housed inside a compact modular vessel with limited piping, holds significant importance from the perspectives of safety, security, and safeguards. This design approach ensures limited access to the nuclear core and fuel components, which is particularly crucial for isolated microgrids with limited security personnel. Underground siting configurations are also crucial to limit access to nuclear materials. Battery-type reactor concepts that can operate throughout their lifetime without the need for refueling are particularly suitable for isolated microgrids that face higher risks of intrusion.

Although the characteristics of SRs discussed above make them highly suitable for microgrid deployment, there are still several issues that need to be addressed concerning technology, deployment, and the supply chain [49]. These include considerations such as control-room staffing and human-factor engineering for multimodule plants, the adaptability of existing codes and standards, manufacturing approaches for novel components, and back-end solutions for fuel-cycle management. The industry and regulatory bodies are actively engaged in ongoing discussions and deliberations to tackle challenges related to the implementation of SRs in microgrids.

Table 3-1 presents a list of key design parameters for SR technologies, specifically relevant to microgrid operations. The information is obtained from various sources including IAEA ARIS database [17] and Nuclear Energy Agency (NEA) dashboard [23]. The IAEA ARIS database compiles design information provided by various vendors of advanced nuclear technologies. The NEA dashboard gathers publicly available information on advanced nuclear designs and offers guidance for selecting SR technologies for a wide range of applications. It uses metrics related to licensing, financing, supply chain, siting, fuel, and stakeholder engagements as a guideline. The parameters presented in Table 3-1 play a crucial role in identifying the most suitable microgrid applications. It is necessary to quantify these design parameters for the SR technologies discussed above to facilitate selection and scenario development for microgrid implementation.

Table 3-1 Design parameters for SRs [5], [9], [17], [49]

Reactor Name	CAREM	NuScale [28]	MARVEL [50]	eVinci	U-Battery [51]	MMR[45]	Aurora [52]
Technology Type	iPWR	iPWR	Liquid Metal	Liquid Metal (Heat Pipe)	HTGR	HTGR	Liquid Metal (Fast Spectrum)
FOAK Timeline	2026	2029	2024	2024	2028	2026	2025
Siting Approach	Land, Multi-module	Land, Multi-module, Under-water	Land	Land, Mobile	Land, Under-ground	Land, Multi-module	Land
Thermal Rating (MWth)	100	250	0.1	13	10	15	4 to 150
Electrical Rating (MWe)	30	77	0.02	3.5	4	10	1.5 to 50
Process Output Temp (°C)	326	321	548	750	710	630	500
Fuel Type	UO_2 Pellets, (Hexagonal)	UO_2 Pellets (Hexagonal)	UZrH	TRISO	TRISO Prismatic	TRISO Prismatic	U-Zr Alloy (Recycle)
Enrichment (%)	3.1	<4.95	<19.75	5-19.75	<20	19.75	<20
Reactor Control	Control Rod	Control Rod, Boron	Control Drum	Ex. Core Control Drum	Control Rod	Control Rod, Negative reactivity feedback	Control Drum, Negative reactivity feedback
Refuel Cycle (months)	14	18	60	>36	60	240	120-240
Design Life (y)	40	60	40	40	30	20-40	>40
Plant area (m^2)	36,000	140,000[h]	8.9	<4,000	350	13,000 (No EPZ)	<10,000
Balance of Plant	Steam Turbine	Steam Turbine	Stirling Engine	Gas Turbine (Open Cycle)	Gas Turbine (Nitrogen)	Steam Turbine	SCO_2 Rankine Cycle
Target Energy Products	Electricity, Heat, Desalination	Electricity, Heat	Electricity, Heat	Electricity, Heat	Electricity, Heat, Hydrogen	Electricity, Heat, Hydrogen	Electricity, Heat
Other Relevant Unique Features	-	Load Follow & Frequency Control Capabilities	-	Autonomous Operation-Load Follow and Frequency Control	-	Molten Salt loop Isolating Reactor & Turbine	Water not required
Potential Microgrid Use	Remote, Coastal	Grid, Industry, Renewable	R&D, Testing	Remote, Mining, Military	Remote, Industry	Remote, Municipal, Industry	Municipal, Remote

[h] This is for VOYGR-12, a 12-unit configuration of NuScale SMR plant with total electrical capacity of 924 MWe.

4. ASPECTS OF MICROGRID APPLICATIONS

4.1 Microgrid Characteristics

Microgrids are purpose-driven systems that serve customers and the grid. They are emerging as important entities in the power-delivery system. They are designed with specific objectives in mind, such as resiliency: providing electricity to remote communities or islands with limited access to a centralized energy network and ensuring the availability of power to critical loads during outages by leveraging local generation resources. Advanced microgrids are designed to meet local demand while also seeking opportunities to generate revenue by selling electricity or offering grid services. They are interactive with utilities and the market. Regardless of the purpose or operational constraints, microgrids typically consist of controllable energy generation, energy storage and loads, all within a well-defined electrical and geographical boundary. In the context of this report, microgrids can encompass both electricity and heating loads. Several key characteristics that are essential for making informed microgrid planning decisions are outlined below.

- **Financial Capacity**: Every microgrid has financial constraints, with limitations on the cost of technology it can afford. These cost limitations play a crucial role in the selection and implementation of energy generation, storage, and control systems, ensuring that the microgrid remains economically viable and sustainable over the long term. This encompasses securing the necessary initial funds for resource investment and maintaining a steady stream of funds for ongoing O&M activities.
- **Location and Accessibility:** The location of a microgrid is an important factor in making the planning decisions regarding technology. For instance, for microgrids located in a remote area, transportability becomes a significant consideration. The technology capable of being transported with available means and operating with fuel-transport constraint would be ideal. Similarly, for a microgrid intended for a marine application, it is essential to consider marine-based technologies that are specifically designed to withstand the unique challenges posed by offshore conditions.
- **Size:** The electrical size of a microgrid is a crucial consideration when selecting appropriate technologies. Not all generation technologies are inherently scalable. A larger microgrid can accommodate larger and more-efficient generation units that may have limited scalability. Conversely, smaller microgrids must opt for scalable generation or storage technologies.
- **Demand Characteristics**: It is crucial to understand the type of demand microgrids entail. This understanding will guide in selection, sizing, and hybridization of technologies. For example, understanding whether a microgrid is focused solely on electricity, heat, or both in combination will help facilitate decisions on thermal nuclear-generation assets in the system. The demand profile is a key factor in determining the appropriate sizing of energy generation and storage systems. If the demand exhibits high volatility, the inclusion of flexible energy-storage solutions becomes particularly advantageous. Energy-storage technologies such as batteries or TES can effectively balance demand peaks by storing excess energy during periods of low demand and releasing it during peak demand periods.
- **Reliability and Resilience Needs:** It is crucial to assess the reliability and resilience needs of the customers or loads that the microgrid serves. Different types of loads may have varying requirements for power quality and stability. For instance, industrial loads with stringent requirements and low tolerance for power-quality degradation necessitate the implementation of generation and sufficient storage technologies that have the highest probability of meeting the minimum threshold. This may involve the use of redundant power-generation sources, energy-storage systems for backup power, and advanced control systems to swiftly respond to any disturbances or faults.
- **Microgrid Life Span**: It is important to investigate the expected duration of the application. If the microgrid is intended for temporary use, such as for emergency response or event-specific purposes,

mobile generation technologies would be more suitable because mobile SR technologies can easily be transported and deployed to meet short-term energy needs in various locations. On the other hand, if the microgrid is intended to serve a growing community or a long-term energy need, it is advisable to consider technologies that support the incremental addition of modules. This allows for scalability and flexibility, enabling the microgrid to expand as the community's energy demand increases over time. Such modular technologies can be added gradually, matching the pace of community growth and ensuring efficient utilization of resources.

- **Area Constraint**: It is crucial to investigate the area constraints associated with the deployment. In urban locations where space is limited, it becomes impractical and expensive to consider power-generation technologies that require a large footprint or necessitate the allocation of significant EPZs. Such technologies may not be feasible due to the high cost or unavailability of adequate space.

4.2 Electric Applications

Electricity is one of the major energy products generated and consumed in a microgrid. Microgrids strive to provide reliable and sustainable electricity to meet the demand of their connected consumers. These electricity needs can include powering various residential, commercial, and industrial loads, such as lighting, appliances, machinery, air-conditioning, data centers, and critical infrastructure. Electricity is produced by different energy resources including conventional thermal generation, renewable-energy resources such as wind, photovoltaics, hydropower, and SRs. These generation resources can be dispatchable or non-dispatchable. The generation resources with a microgrid are optimized to ensure an economic, efficient, and reliable power supply.

Microgrids may experience imbalance between electricity generation and demand. In cases where microgrids have access to the main electrical grid, they interact with it to obtain additional electricity during shortages or supply surplus electricity when it is available. The energy storage can be hosted alongside generation technologies to maintain the balance between generation and consumption. Energy storage, such as batteries, can effectively provide this balance by storing energy during periods of excess generation and releasing it during peak demand. Furthermore, energy-storage systems can facilitate cost-effective interactions with the grid based on electricity price.

4.3 Non-Electric Applications

Microgrids often have both electricity and heating demands. Heating demand may arise from localized industrial or commercial units requiring high-quality process heat or from residential areas situated in regions with severe winter climates, where substantial space and water heating are needed. Many industries already possess localized heating resources to meet their specific heating requirements. Unlike electricity, heat cannot be transported over long distances. Therefore, heat production should ideally occur locally, within the microgrid's boundaries. While electric heating is one possible option, it is generally not cost-effective and may not be suitable for different industrial processes.

For microgrids with significant heating requirements, it is beneficial to explore thermal or nuclear-generation alternatives that can efficiently provide both clean heat and electricity cost-effectively. This strategy not only lowers energy costs associated with heating processes, but also contributes to the decarbonization of industrial, commercial, and residential heating sectors, which are significant contributors to global greenhouse gas (GHG) emissions. Furthermore, by having the option to use the produced thermal energy for heating applications and electricity generation, the generation unit gains additional flexibility to optimize operations and reduce the overall operational costs of the integrated system.

The choice of generation technologies depends on the specific heating application. Figure 4-1 illustrates the temperature ranges suitable for different heating applications [5],[53]. For applications requiring high-temperature heat, thermal or nuclear technologies capable of providing such temperatures should be considered. For instance, microgrids incorporating high-temperature electrolysis plants would greatly benefit from high-temperature SR technologies like the high-temperature gas-cooled or molten-salt reactors. Conversely, low-temperature applications such as district heating and pulp and paper production are better served by employing low-temperature technologies like water-cooled SRs or solar thermal systems.

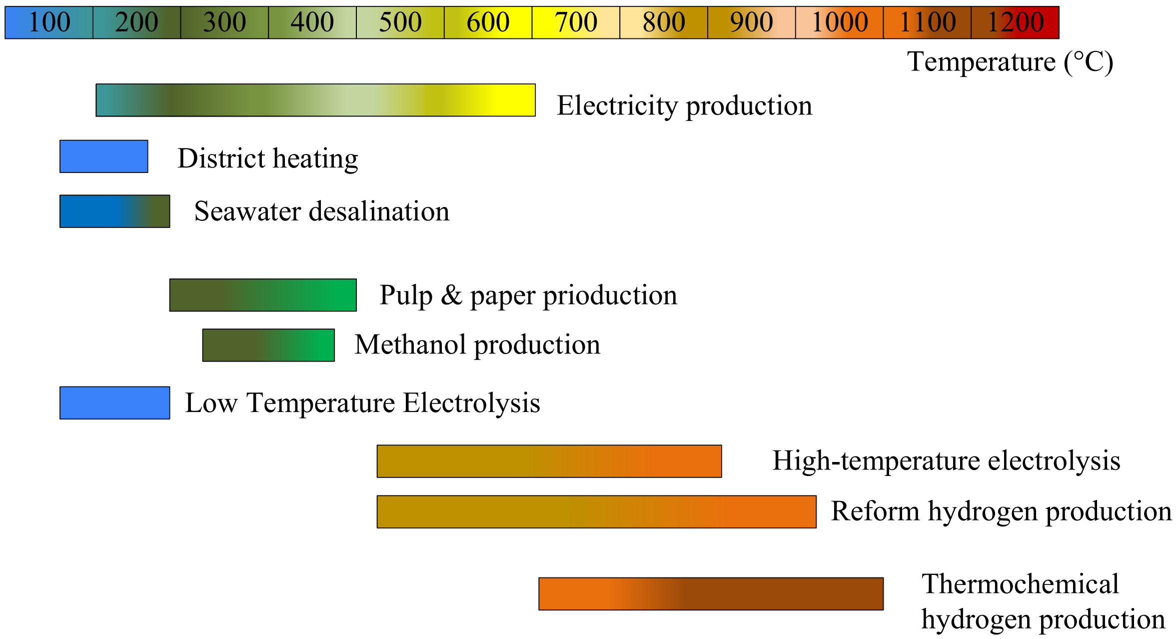

Figure 4-1. Temperature requirements of potential microgrid applications.

TES plays a crucial role in these energy systems. As discussed in Section 3.5.1, TES can be implemented in various configurations to decouple the processes of heat generation and consumption. This enables efficient energy balancing and flexibility in both the heat and electricity domains. Previous studies have demonstrated that integrating TES into heat and energy systems enhances the flexibility of traditional power plants operating in baseload or semi-baseload modes. The inclusion of energy storage allows these integrated systems to provide power variations on more-frequent basis to meet load-following requirements while also facilitating the integration of variable renewable-energy resources.

4.4 Approach to Implementing SRs in Microgrids

4.4.1 Capabilities and Limitations of SRs in Microgrids

The capabilities and limitations of SRs in microgrids are manifested in three respects: nuclear unit (thermal), turbine (mechanical), generator (electricity). Normally, an SR produces heat that can be used for district heating or for driving a steam turbine, which runs a synchronous machine.

The electrical-power unit in a conventional SR is the rotating synchronous generator. From the perspective of integrating SRs in microgrids (or any other aggregations of distributed energy resources), primary consideration must be given to the performance of the SR system in generating and producing electric power. Alternatives for the conversion of SR thermal power to electrical power can be investigated. Considerations would include controllability, efficiency, flexibility, and dynamic performance of the electric-power generator.

4.4.2 SR Operation—Control and Modeling

The SR should be examined as a generating asset in a microgrid, integrating in varying combinations of (wind and solar) renewable-energy resources, storage, and flexible loads. The SR is a “must run” unit, with flexibility constrained by the allowed rate of change in power variation. Balancing capability for renewables generation variations, electrical storage (batteries), and flexibility within the microgrid merit investigation.

The management of the electrical output of the SR by the microgrid energy-management systems (EMS, dispatch function) in grid-connected and islanded modes—islanding, disconnecting, reconnecting, transitions—is a major operational consideration for investigation. Examples of operational considerations are the behavior of thermal- and electric-power generation within the microgrid and the differences in the dynamic capabilities, power ramp rates, and cycling, as well as their impact on operations over long durations.

4.4.3 SR Operations with Storage for Multiple Scenarios

Different operating modes and conditions for an SR and energy storage working together should be investigated. This is one of the first applications to pursue. This concerns both battery energy storage and heat storage. The alternative operations of SRs for each need to be explored. The technical requirements for moving from thermal output to electric output and vice versa need to be established.

4.4.4 SR Response to Signals for Dispatch for Market Participation and Grid Services

SRs are best suited to be run at constant power output. However, they may be required to dispatch in response to signals from system operators. Frequency support, combined with demand curtailment, is included in this application. The interaction of the controls for the SR and its generating unit with the microgrid EMS (and eventually with distribution operations) merit attention.

4.4.5 Compliance with Functions within Standards for Microgrids

Applications should be viewed from two main perspectives, focusing on internal operation in the microgrid and provision of grid services across the point of interconnection. Both will involve setting up use cases for how the SR would operate within a microgrid and in response to grid requirements. Here the EMS becomes central to the examination of applications, with performance of the functions required in IEEE Std 2030.7, 2017 [1], and IEEE Std 2030.11, 2021 [54], being paramount.

The suitability of an SR as a generator in a virtual power plant, and its flexibility within an aggregation of distributed energy resources is important as well.

4.4.6 Modeling and Simulation Tools

The Xendee microgrid-modeling tools with the SR model are uniquely designed for modeling and simulation of multiple operating scenarios. They capture the unique features of the SR as they relate to microgrids. Once these operating scenarios are defined, the modeling and simulation tools can be used to scale the results from research experiments on an actual small-scale SR, such as MARVEL.

5. FUTURE WORK

In the future, an external module will be created to generate parametric inputs derived from raw-design information provided by different SR technology vendors as a supplemental resource to the SR model and the Xendee platform. This module will consider all possible characteristics of SRs, including reactor type, fuel technology, fuel-enrichment process, cost of maintenance of coolant and moderator, and waste-handling and storage options. Additionally, an SR database will be developed to support technology selection in microgrid studies, specifically focusing on the most-promising SRs. Furthermore, the SR model in Xendee will be enhanced with additional features. These include incorporating high- and low-heat end uses, distinguishing them based on the heat-extraction point and the heating-load application. The model will also encompass the design and configuration of heat utilization with TES. Furthermore, the enhancements will include considering perimeter security for siting purposes in the Xendee GIS model.

The developed SR model will be used to investigate several microgrid applications. This will involve examining the price target and timeline for SR technology to become sufficiently close to cost-competitive with natural-gas generators such that other benefits (e.g., resilience, reduced supply chain for fuel) or avoided costs can justify any added expense. Additionally, the role of a generation mix comprising SRs, renewables, and storage in addressing transmission congestion issues will be explored. The analysis will also assess the capability of TES to support integrated heat and electricity applications. Furthermore, the research will involve selecting components, such as power-conversion systems and TES, as well as exploring design configurations within nuclear systems, including retrofitting existing power-conversion technologies for advanced SRs. Cost targets will be established to ensure the timeline for SRs will be applicable in various microgrid applications, such as supporting DoD/DOE missions, providing energy to underserved remote communities, offering resilient services to vulnerable parts of the grid and critical infrastructures, and collaborating with renewables to deliver carbon-free electricity to the grid.

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APPENDIX A
SR MODELING IN XENDEE PLATFORM

A-1. Parameters for SR Model

Category	Parameters	Description
Costs	Investment Costs	Total capital cost from start to completion with economies of scale ($)
	Electrical Efficiency	O&M cost excluding fuel-related costs (e.g., staffing, repairs) ($)
	Fuel Cost	Discrete front-end and back-end fuel costs ($)
	Decommissioning cost	Cost to decommission the plant ($)
	Waste handling cost	Cost to dispose/reprocess spent fuel after interim storage ($) (Is part of back-end fuel costs)
Life Parameters	Fuel life	Refueling cycle (years)
	Plant life	Plant years of operation (years)
Efficiency and Performance	Electrical Efficiency	Efficiency to convert reactor heat to electricity (thermodynamic cycle, turbine, generator)
	High-grade heat quality	Temperature of process heat (°C) or grade
	Mid-grade heat quality	Temperature of mid-grade heat (°C) or grade
	Low-grade heat quality	Temperature of low-grade heat (°C) or grade
Operational Constraints	Minimum up time	Minimum time to stay online (hours)
	Minimum down time	Minimum time to stay online (hours)
	Minimum loading	Minimum reactor thermal power output (% of RTP)
	Hold time	Minimum time before changing power level (hours)
	Maneuvering cycle limits	Number of semi-base load maneuver cycles (e.g., x number of <20%, and y number for >20% power change in a day/ month/year/life)
	Power Change limits	Ramp rates for different range of reactor power change. (e.g., 5%/min for >10%, 20%/min for <10%)
	Ramp rate limits	
	Operation Schedule	Ramping period and hold periods for normal operation

A-2. Small Reactor Technologies Reported by IAEA Applicable for Microgrid Applications

A-2.1 Water Cooled

The KLT-40S, a floating SR unit, is the first to be deployed in the water-cooled category. It started commercial operation in Pevek, Russian Federation, in May 2020 (Figure A). Water-cooled SRs are likely to be the first to be deployed commercially in the US (Figure A), with NuScale leading the way with significant government support. Each NuScale unit is sized at 77 MWe.

Figure A-1. Marine-based water-cooled SRs suitable for microgrid applications [5].

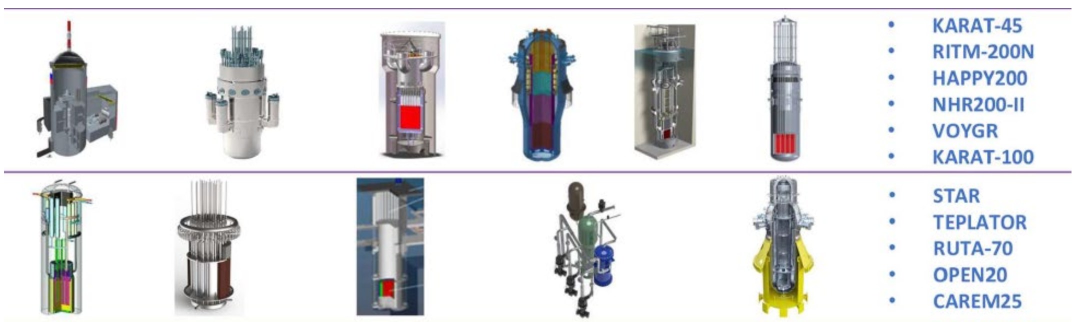

Figure A-2. Land-based water-cooled SRs suitable for microgrid applications [5].

A-2.2 Liquid-Metal Cooled

EBR-I, the first nuclear reactor developed for electricity production, was a metal-cooled reactor using NaK coolant. 4s is the fast reactor developed by Toshiba Corporation and Central Research Institute of Electrical Power Industry (CREIPI), Japan. It employs sodium coolant, metal fuel (U-Zr alloy) with enriched uranium, and has a significantly high refueling time. MARVEL uses sodium-potassium eutectic as a coolant with hydrogen as a moderator. Westinghouse’s eVinci and Oklo’s Aurora both use sodium coolant in the sealed heat pipe—the former is an intermediate-spectrum while the latter is a fast-spectrum reactor. SEALER-55 is a lead-cooled SR developed by LeadCold, Sweden, whereas MicroURANUS being developed by Ulsan National Institute of Science and Technology (UNIST), Republic of Korea uses LBE for coolant (Figure A).

Figure A-3. Liquid-metal-cooled reactors suitable for microgrid applications [5].

A-2.3 Liquid Metal Heat Pipe Cooled

Mobile-Very-small reactor for Local Utility in X-mark (MoveluX) is a 10 MWt heat-pipe cooled reactor design developed by Toshiba targeted for electricity, hydrogen, and high-temperature heat and suitable for off-grid electricity applications. It uses molten sodium coolant and calcium hydride as moderator and hexagonal silicide (U_3Si_2) fuel assembly. eVinci is another heat pipe reactor being developed by Westinghouse, leveraging the MegaPower technology developed by LANL. It is planning to use TRISO particle fuel (Figure A).

Figure A-4. Heat-pipe cooled reactors suitable for microgrid applications [5].

A-2.4 High Temperature Gas Cooled

Xe-100 is a pebble-bed HTGR being developed by X-energy, USA, featuring a continuous refueling system providing a final average burnup rate of 165, 000 MWd/tHM. AHTR-100 is a 50 MWe pebble-bed HTGR developed by ESKOM Holdings, South Africa. U-battery (10 4 MWe) by Urenco, United Kingdom and Holos-Quad (10 MWe) by HolosGen, USA are some of the reactor concepts with TRISO fuel embedded in a graphite structure. HolosGen is based off the General Electric's nuclear turbojet concept from 1960s (Figure A).

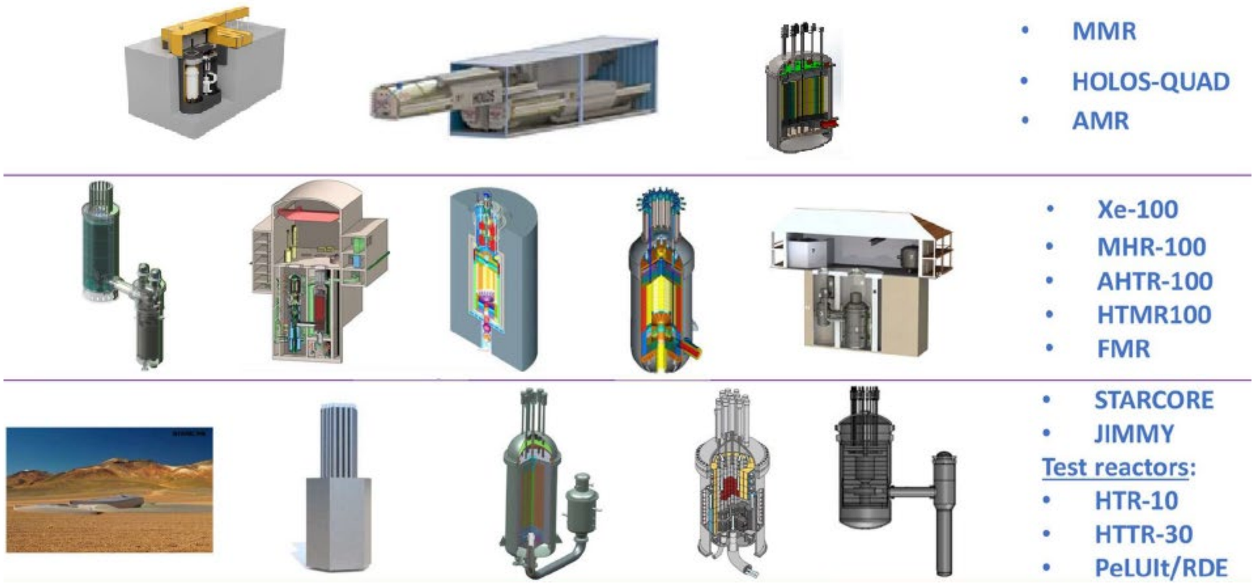

Figure A-5. High-temperature gas-cooled reactors suitable for microgrid applications [5].

A-2.5 Molten Salt Cooled

Mk1 PB-FHR is a 100 MWe pebble-bed reactor MSR with TRISO particle and graphite core, using Li_2BeF_4 molten-salt coolant. Waste Burner is a 20 MWe MSR by Copenhagen Atomics which uses molten-salt fuel with LiF-ThF_4. TMSR-LF1 is a 2 MWt liquid fueled thorium-based MSR developed by China (Figure A).

Figure A-6. MSRs suitable for microgrid applications [5].