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United States–Brazil Joint Study: A Preliminary Assessment of Opportunities and Challenges for Small Modular Reactors in Brazil

February 2023

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ABSTRACT

This report supplies the technical information to enable a broader understanding of different technology choices for nuclear reactors in Brazil. The assessment characteristics of this process include reactor technology, economic costs for deployment, and regulatory analyses of small modular reactors, advanced reactors, and microreactors. The analysis documented in this report provides economic and technological information to assist Brazil, whose official indicative scenarios show an increase in operating nuclear power from 2 Gigawatt in 2022 to 8–10 Gigawatt by 2050, in policy making and long-term energy planning. To protect company proprietary information, the information in this report was limited to publicly available information and therefore can only inform preliminary reactor technology assessments. This report does not recommend or endorse any specific reactor developer or technology.

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EXECUTIVE SUMMARY

Idaho National Laboratory (INL), in collaboration with the United States (U.S.) Department of Energy and the Brazilian Empresa de Pesquisa Energética (EPE), performed a technology, economic, and regulatory assessment of small modular reactors and advanced reactors based on characteristics of interest to Brazil. Brazil is considering, in official energy indicative scenarios, increasing operating nuclear power, from 2 GW in 2022 to 8–10 GW by 2050. Per EPE, the types of reactors under consideration by Brazil include small modular reactors, microreactors, and advanced reactors. This project was intended to address areas of interest, criteria, and priorities as defined by EPE in considering nuclear reactor technologies that best suit the country's long-term energy needs utilizing publicly available information.

The main objective of this project was to collaborate directly with EPE to gather information to help Brazilian policy makers and regulators in assessing a comparisons of energy sources and developing a roadmap for nuclear policy implementation. Multiple meetings were held to understand the needs of the Brazilian energy market and technical issues being considered. After much discussion and prioritization by EPE, the scope of the project focused on:

1. Developing attributes and collecting data based on EPE-selected parameters on reactor concepts
2. Gathering data and tools to assess the economics of reactor designs
3. Identifying and assessing potential technical issues for reactor applications in Brazil
4. Identifying licensing- and safety-related cost reduction opportunities
5. Evaluating the broader, longer-term trade-offs for using reactors.

This project was not intended to recommend any specific reactor design over another; rather, it was intended to provide information on reactor technologies for consideration by policy and decision makers in Brazil. All information used in this project for the technology review was obtained from publicly available published data. Other information regarding Brazil's infrastructure was provided by EPE. This report does not recommend or endorse any specific reactor developer or technology.

Technical Area 1: Developing attributes and collecting data based on EPE-selected parameters on reactor concepts

For the first technical area, preferable attributes were provided by EPE. Examples of the attribute types initially provided by EPE for consideration included: plant construction time, design maturity, power ramping capability, minimum allowable power output, infrastructure for spent fuel, cooling designs, and siting requirements. Based on these attributes, INL collected data on potential reactor concepts from available published data and further refined the data to identify overall characteristics that can be used to evaluate candidate reactor technologies against other Brazilian energy sources. These characteristics focused on topics such as technical readiness, construction modularity, and readiness from the perspective of the supply chain, regulatory, operational, and commercial market. Work in the first technical area resulted in a review and comparison of the EPE-provided attributes and characteristics of specific design concepts for U.S.-based developers and references for those reactor technologies. This information was then evaluated for relevant details applicable to the Brazilian technology review process, including the evaluation of technological trade-offs based on reactor concept characteristics. After an evaluation of available data and further INL collaboration with Brazilian EPE staff, two additional characteristics were added to meet the needs of the Brazilians: reactor design modularity and market readiness. These characteristics combined multiple topics (see above) and were evaluated using a modified technology readiness level (TRL) (from 1 [low] to 9 [high]) that was developed and agreed upon by INL and EPE.

Outcome for Technical Area 1: The data collected by INL staff was used in a technology review and evaluation. The technologies identified by EPE as being of most interest for further study were used for the other following technical areas being assessed. EPE selected four design categories for further assessment. A microreactor was included to meet EPEs priority for modularity. A thorium-fueled reactor was also chosen as a priority for EPE based on Brazil's domestic thorium resources. The other two designs, a light-water-cooled small modular reactor (SMR) and high-temperature gas-cooled SMR, were chosen by EPE based on the data presented by INL on predicted market readiness and construction modularity of current U.S.-based SMR designs. Additional assessment areas included safety, economics, market conditions, licensing, and long-term aspects, such as spent fuel storage.

Technical Area 2: Gathering data and tools to assess the economics of reactor designs

For the second technical area, INL gathered information to assess the economics of the evaluated reactor designs. This activity used the results of the first outcome and additional public information to compile relevant cost information on reactor concepts and to identify potential economic analysis methodologies and strategies applicable to reactor development. Factors that were considered included factory fabrication, modularity, and standardization. Based on the technology review performed in Technical Area 1, EPE requested that water-, gas-, molten-salt-, heat-pipe-, and liquid-metal-cooled reactors be considered.

Outcome for Technical Area 2: The outcome yielded an approach known as the Regional Economic Impact Analysis. This analysis assists EPE in performing a reactor macroeconomic study evaluating reactor economic modeling and analysis and includes an evaluation of direct, indirect, and induced impacts. This study will help the Brazilian policy and decision makers identify the potential impacts of reactors on local, regional, and national economies.

Technical Area 3: Identifying and assessing potential technical implications from reactor applications in Brazil

For the third technical area, INL identified and assessed the technical attributes of reactor technologies that could arise during deployment in Brazil for a variety of technical elements. Deployment indicators (provided by INL and discussed with EPE) include design implications that should be considered, including energy market growth, investment opportunities, grid conditions and capacities, and energy security. These deployment indicators use a Favorable, Neutral, or Unfavorable rating. Each of these deployment indicators was used to grade the reactor technologies, thereby providing an evaluation of the reactor technologies that may most positively affect societal metrics in Brazil.

Outcome for Technical Area 3: This approach produced a list of potential strengths and weaknesses of reactors based on EPE attributes and their technical basis.

Technical Area 4: Identifying licensing- and safety-related cost reduction opportunities

For the fourth technical area, INL evaluated Brazilian licensing-related information that would apply to the development of new nuclear plants and reviewed the current Brazilian nuclear regulatory structure to understand regulatory processes and procedures, including the control and protection of nuclear materials, environmental regulations, licensing of nuclear facilities, quality assurance, in-service inspection, and siting. During this evaluation, updates to procedures that would provide a similar level of protection to public safety and security or lead to decreased costs associated with the operation of reactors were noted. This included the development of a technology-inclusive, risk-informed regulatory basis for the licensing of reactors similar to the approaches currently under development in the U.S. This risk-informed regulatory licensing process would facilitate enhancements in the licensing of selected reactors by focusing on new design features, such as passive cooling systems.

Outcome for Technical Area 4: The outcome of this review provided potential updates for consideration for public safety and security with reactor operation.

Technical Area 5: Evaluating the broader, longer-term trade-offs for using advanced nuclear reactors

For the fifth technical area, a lifecycle approach of advanced nuclear reactors was evaluated by considering the broader, longer-term trade-offs of these nuclear technologies. Situations were identified where the use of reactor technologies may diverge from the current light-water reactor (LWR) approaches. For example, the reactor technologies identified via the Brazilian technology review process represent a very broad range of reactor design and fuel concepts, and as a result, some of the designs, fuel forms, and reactor operational constructs will be more defined than others. In addition, some long-term aspects (e.g., decommissioning strategies, spent fuel processing) should be taken as presumptive.

Outcome for Technical Area 5: This outcome identified situations where the use of advanced nuclear reactor technologies may diverge from current LWR approaches.

Project Deliverable

This report was developed that summarized the EPE reactor attributes to identify overall characteristics that can be used to evaluate candidate reactor technologies against other energy sources. These attributes provided the basis for the technology review economic modeling and analysis, updates for consideration in the regulatory process for reactor operations, and some areas where reactors may diverge from current LWR approaches. This report is intended to address some of the EPE inquiries on reactors regarding technical readiness, construction modularity, and readiness from the perspective of the supply chain, regulatory, operational, and commercial market. Also identified in the report are additional follow-on activities to further support reactor deployment in Brazil when technologies have been further vetted, including local technology assessments (e.g., environmental, emergency planning zones, siting, development of a risk-informed regulatory licensing process, etc.). These areas are critical for EPE and Brazilian policy and decision makers to enable energy security and independence.

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ACKNOWLEDGEMENTS

Idaho National Laboratory greatly appreciates the opportunity to collaborate with Empresa de Pesquisa Energética on this project and be able to engage with them as Brazil moves forward to increase their nuclear power generation. Idaho National Laboratory would also like to thank the Department of Energy Office of International Affairs and Office of Nuclear Energy Office of International Nuclear Energy Policy and Cooperation for their outreach and support of this project.

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ACRONYMS

AR	advanced reactor
ARIS	Advanced Reactors Information System
BWR	boiling-water reactor
CBA	cost-benefit analyses
CTEA	Comparative Techno-Economic Assessment
DOE	Department of Energy
ECR	environment, cost, reliability
EIA	Economic Impact Assessment
EPE	Brazilian Empresa de Pesquisa Energetica
EPZ	emergency planning zones
FHR	fluoride high-temperature reactor
FOAK	first-of-a-kind
GCR	gas-cooled reactor
HTGR	high-temperature gas reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
LFR	lead-cooled fast reactor
LILW	Low- and Intermediate-Level Waste
LR	large reactors
LWR	light-water reactor
MR	microreactor
MSR	molten-salt reactor
NRC	Nuclear Regulatory Commission
NOAK	nth of a kind
PDI	Porto do Itaqui Coal Power Plant
PHWR	pressurized heavy water reactors
PWR	pressurized-water reactor
RW	radioactive waste
SMR	small modular reactors
SNF	spent nuclear fuel
SFR	sodium fast reactor
TRL	Technology Readiness Level
VRE	variable renewable energy

United States–Brazil Joint Study: A Preliminary Assessment of Opportunities and Challenges for Small Modular Reactors in Brazil

1. INTRODUCTION

Idaho National Laboratory (INL) is working with organizations including the United States (U.S.) Department of Energy and Brazilian Empresa de Pesquisa Energetica (EPE) to perform a technology, economic, and regulatory analysis of small modular reactors (SMRs), advanced reactors (ARs), and microreactors that will provide technical information to assist the Brazil's policy making and long-term energy planning, whose official indicative scenarios show an increase in operating nuclear power, from 2 Gigawatt (GW) in 2022 to 8–10 GW by 2050.

The program objectives for this work are to:

- Inform U.S. nuclear suppliers and investors about opportunities and barriers observed for SMRs in Brazil
- Make recommendations to help Brazilian policy makers and regulators develop an attractive and competitive environment for SMRs in Brazil
- Serve as a roadmap to guide Brazilian decision makers to develop a competitive and attractive environment for SMRs in Brazil within the referenced timeframe of 2050 and the perspective to add 8–10 GW of nuclear generation capacity.

The work scope settled on five outcome areas:

- Outcome 1: Developing screening criteria and collect data on SMR concepts
- Outcome 2: Gathering data and tools to assess the economics of SMR designs
- Outcome 3: Identifying and assess technical implications from SMR applications for Brazil
- Outcome 4: Identifying licensing and safety-related cost reduction opportunities
- Outcome 5: Evaluating the broader, longer-term trade-offs for using SMRs.

These five outcome areas above are addressed in the technical analysis described in Section 2 of this report. The conclusions are then presented in Section 3.

2. TECHNICAL EVALUATION

2.1 Outcome 1: Develop Screening Criteria and Collect Data on Small Modular Reactors Concepts

The goal of Task 1 was to gather information to assist EPE with selecting a few reactor designs that fit their needs. This required coordination between INL and EPE to determine the highest priorities for EPE and to compile the relevant public data for each design. Task 1 was completed in three parts: initial reactor technology review and information collection, EPE determination of high-priority design characteristics, and design assessment based on criteria. This led to a technology review list of four reactor designs from EPE.

2.1.1 Initial Reactor Technology Review

This section first presents an overview of reactor technology by coolant type. The overview provides a brief description of the differences in reactor families by coolant type to give the reader a clear understanding of the terminology used repeatedly in this report. A map from the International Atomic

Energy Agency (IAEA) that shows all the SMR and modular reactor (MR) designs being developed around the world in 2020 is also included. After the overview of reactor technology is presented, this section presents a discussion on the availability of public data for SMR designs and the methodology of data collection used.

2.1.1.1 Reactor Families by Coolant Type

This subsection groups and introduces reactor families by coolant type: water, gas, molten salt, and liquid metal. One microreactor concept is also included based on EPE's interest. Liquid metal as a SMR coolant type is discussed only to represent all the possible coolants and is not discussed further based on EPE's interests. A discussion of water cooled as the only Generation III+ (Gen III+) technology with similarities to water-cooled large reactors (LRs), specifically leveraging proven light-water reactor (LWR) concepts is included. The other three reactor coolant types, gas, molten salt, and liquid metal, are all Gen IV reactor technologies. These Gen IV reactor technologies are expected to change the shape of nuclear energy. As shown in Figure 1, SMRs and MRs are being developed around the world by universities, governments, public-private partnerships, multinational partnerships, and more.

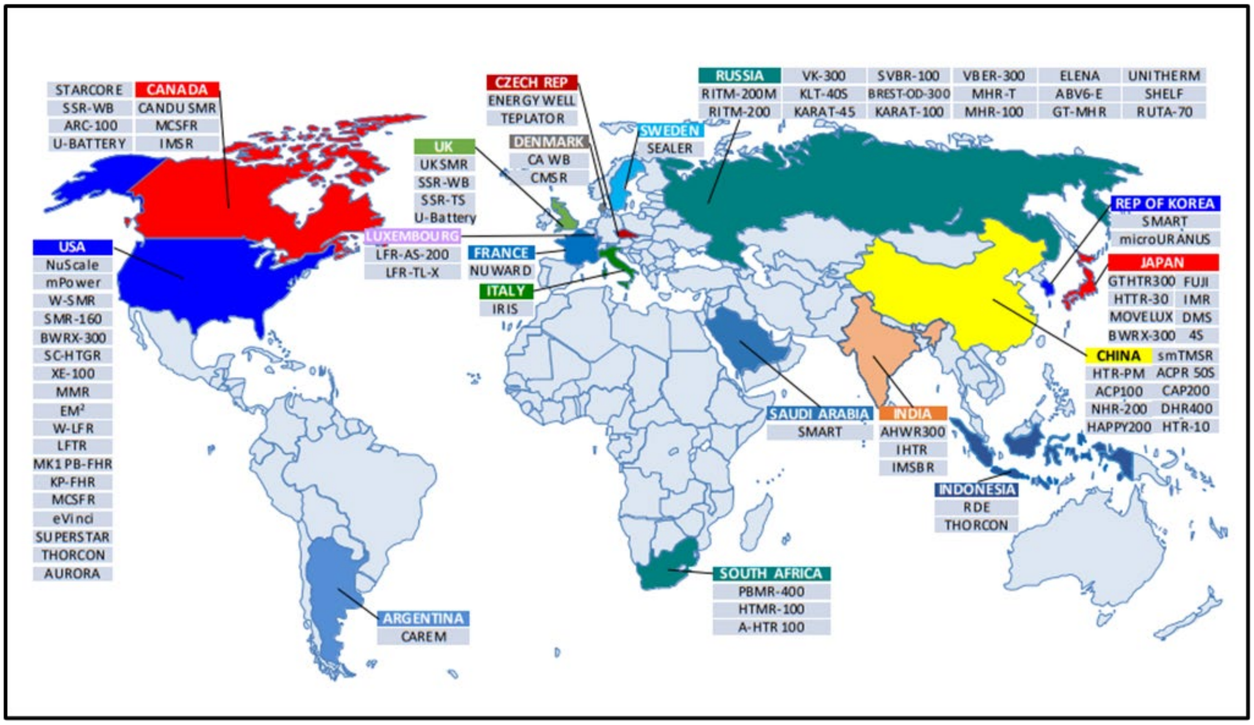

Figure 1. Map of SMR concept development (IAEA 2020).

1. Water-cooled reactor
   Most current LRs around the world use water as a coolant. In these designs, water also acts as the moderator, which is a substance used to slow down fast (fission spectrum) neutrons for better fuel atom absorption. The water used is either light water or heavy water. Heavy water differs from light water (normal water) in its chemical makeup and is referred to as deuterium or D_2O, where the hydrogen atoms have an extra neutron (Nuclear Innovation Alliance 2021). There are three main water-cooled designs, pressurized-water reactors (PWRs), boiling-water reactors (BWRs), and pressurized heavy water reactors (PHWRs).

2. High-temperature gas-cooled reactor (HTGR)
   Gas-cooled reactor technology uses gasses, including helium or carbon dioxide, as the cooling and heat transfer (Nuclear Innovation Alliance 2021). The high-output temperatures allow heat from the

reactor to be used in processes that other reactor designs, like BWRs, cannot meet, making them desirable for industries including some types of desalination and hydrogen production.

3. Molten-salt reactor (MSR)
   MSRs use molten chloride or fluoride as a coolant, sometimes mixing the fuel in with the coolant. These coolants are used because of their opportunity for passive safety measures. If the reactor moves out of operational temperature ranges (i.e., overheats), the fuel can drain into an area where it can solidify and prevent meltdowns.
4. Liquid-metal-cooled reactor
   As the name implies, liquid-metal reactors use materials like a lead-bismuth eutectic alloy, lead bismuth, or liquid sodium as the heat transfer medium. This provides passive safety benefits along with other benefits over water reactors, as these mediums do not slow down neutrons as much as water (Nuclear Innovation Alliance 2021).
5. Heat-pipe-cooled reactor
   Heat-pipe-cooled MRs are included in this analysis alongside SMRs due to the uniqueness of the heat-pipe design and potential for microreactor applications around Brazil. Heat pipes quickly and passively transfer thermal energy across a vacuum from an energy source to an energy sink. The heat source evaporates the transfer fluid, which moves towards the cooler section of the pipe, where it condenses. The condensed fluid then moves back towards the hot side of the pipe through a wick. The reduction in moving parts helps reduce complexity and can reduce maintenance costs.

2.1.1.2 Publicly Available Small Modular Reactor Data

The initial reactors for data collection included all U.S.-based reactors in the IAEA Advanced Reactors Information System (ARIS) database. This was the first step in data collection because designs listed in the database typically had higher data availability because public data was combined into a standard document. Non-SMR designs from ARIS were removed from the list because EPE was specifically looking for a modular design. Unfortunately, ARIS did not include all U.S.-based SMR designs. Later, all SMRs currently listed in the U.S. Nuclear Regulatory Commission (NRC) licensing process were added; although, there is significantly less public data available for these designs. Some of the NRC listed designs were not available in the database, but some were available in the IAEA SMR Book 2020. Note that not all the designs listed are actively being developed or commercialized and are listed only to illustrate various characteristics of the types of SMR technology. Data availability was higher for some less mature technologies than those currently being commercialized, presumably because, as a technology matures, much of the specific technical information becomes proprietary. Because this review is based only on publicly available data, this information was not requested from reactor vendors. EPE was also more interested in SMR designs than microreactors, so only one microreactor design is included in this review summary. The resulting designs of this initial technology review are listed in Table 1.

Table 1. Summary of current U.S.-based SMR designs used in this technology review based on referenced sources.

Acronym	Name	Vendor	Type	In ARIS Database?	Data Availability
BWRX-300	Boiling Water Reactor X-300	GE-Hitachi and Hitachi GE Nuclear Energy	BWR	Yes	High
EM2	Energy Multiplier Module	General Atomics	Gas-Cooled Fast Reactor	Yes	High

Acronym	Name	Vendor	Type	In ARIS Database?	Data Availability
EVINCI		Westinghouse Electric Company	Heat-Pipe Microreactor	No	Low
G4M	Gen4 Module	Gen4 Energy Inc.	Lead-cooled Fast Reactor (LFR)	Yes	Low
KP-FHR	Kairos Power Fluoride High-Temperature Reactor	Kairos Power	Fluoride High-Temperature Reactor (FHR)	No	Low
IMSR-400	Integral Molten Salt Reactor-400	Terrestrial Energy	MSR	Yes	Medium
LFTR	Liquid Fluoride Thorium Reactor	Flibe Energy	MSR	Yes	Medium
MK1 PB-FHR	Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor	University of California, Berkley	MSR	Yes	Medium
MCFR	Molten Chloride Fast Reactor	TerraPower	MSR	No	Low
NATRIUM	—	GE-Hitachi and TerraPower	Sodium Fast Reactor (SFR)	No	Medium
NUSCALE	NuScale SMR	NuScale Power, Inc.	Integral Pressurized-Water Reactor	Yes	High
PRISM	Power Reactor Innovative Small Reactor	GE-Hitachi	SFR	Yes	Medium
PRISMATIC HTR	Prismatic Modular High-Temperature Gas-Cooled Reactor	General Atomics	Gas-Cooled Reactor (GCR)	Yes	Medium

Acronym	Name	Vendor	Type	In ARIS Database?	Data Availability
SC-HGTR	Steam Cycle High-Temperature Gas-Cooled Reactor	Framatome	GCR	Yes	High
SMAHTR	Small Fluoride Salt-Cooled High-Temperature Reactor	Oak Ridge National Laboratory	MSR	Yes	Medium
SMR-160	—	Holtec International	LWR	No	Medium
THORCON	ThorCon	ThorCon U.S., Inc.	MSR	Yes	High
TWR-P	Travelling Wave Reactor-Prototype	TerraPower	SFR	Yes	Low
W-LFR	Westinghouse LFR	Westinghouse Electric Company LLC	LFR	Yes	High
XE-100	—	X-energy	High-Temperature Gas Reactor (HTGR)	No	Medium

2.1.2 Empresa de Pesquisa Energetica Priority Design Characteristics

EPE also presented their selection criteria and indicated a high, medium, or low priority for their specific needs. Some of the data they required for evaluations was publicly available, some data may not be known or available at this time due to the maturity level of the design, and in many cases, data may only be available by contacting the vendor. We reviewed the Brazilian evaluation priorities and returned to EPE with the data availability of each characteristic, as listed in Table 2.

Table 2. Public data availability of high-priority design characteristics for EPE.

Characteristic	Data Availability
Plant construction time	High
Proportion of construction work onsite	Medium
Frequency of refueling and scheduled maintenance outages	High
Average duration of refueling and scheduled maintenance outages	High
Maturity level of the design	High
Ramping up capability	Medium
Ramping down capability	Medium

Characteristic	Data Availability
Minimum up time (tON)	Low
Minimum down time (tOFF)	Low
Minimum allowable power output	Medium
Implications of power variation and part-load operation	Low
Implications of shutdowns	Low
Rotational inertia	Low
CapEx	Medium
OpEx	Low
Capital maintenance expenditure	Low
Decommissioning cost	Low
Infrastructure for spent fuel	High
Maximum expected share of local content	Low
Water consumption	Low
Hybrid or dry cooling designs	High
Technically achievable emergency planning zone	High
Siting requirements considering enhanced safety approach	High
Siting requirements considering enhanced resistance to geological risks	Low
Use of backup heat sources	Low

2.1.2.1 Additional Priority: Thorium-Fueled Reactor Technology

EPE specifically requested that INL include a thorium-fueled reactor design in the delivered reactor design assessments. Brazil has a history of thorium technology development beginning at the start of the country's nuclear program in the 1940s. In the late 1990s, Brazil had an estimated 1.2 million tons of potential ThO_2 resources. More than 170 tons of high-purity thorium nitrate were produced at IPEN, Brazil's nuclear energy research institute until 2004, when changes to the national nuclear policy resulted in the partial decommissioning of the pilot plant. The development of current thorium fueled SMR technologies has reignited national interest in utilizing domestic thorium resources.

2.1.3 Modularity and Market Readiness

Because not all the data necessary to make a decision was publicly available, we suggested EPE choose a few high-priority items to assist with the technology review. They decided to focus on two criteria:

- *Modularity*: SMR designs that will require minimal onsite construction, which will hopefully protect against significant construction delays and unforeseen costs
- *Market Readiness*: Designs that will be ready for commercial use in the near-term—within two decades.

We assessed each of the designs presented here for these two criteria using qualitative methods. We used a modified technology readiness level (TRL) scale to rate each design from 1 to 9. It was difficult to place designs in both categories. For market readiness, some designs were in pre-licensing stages but did not have plans for sited construction or were in the conceptual design stage with little information on their status in the licensing process. The modularity was based on the proportion of onsite construction if available as well as the vendor's description of the construction process and estimated construction time.

2.1.4 Final Reactor Technology Review

Given the above information and through further collaboration with INL, EPE selected four design categories to move forward with technology evaluations for the rest of the technical task areas. Even with the designs selected, there is still not a complete picture related to some technical elements to determine an optimal design for EPE. Further research and vendor contact will be necessary as these designs evolve and mature to make final decisions. Table 3 contains all the available information for EPE's priorities for each technology.

EPE defined the initial criteria for selecting a set of technologies for further exploration. The criteria were largely based on technological maturity and degree of modularity, and EPE requested that thorium technology be included. After applying the criteria, the resulting set of technologies included: a water-based SMR, employing existing LWR technology and therefore with great near-term market potential; a high-temperature gas-cooled reactor design, which will be useful for consideration in heating applications; a heat-pipe-based microreactor; and the requested thorium-based reactor design.

Table 3. Public information available for EPE-selected designs.

Characteristic	Light-Water SMR	High-Temperature Gas-Cooled SMR	Microreactor	SMR Utilizing Thorium fuel
NOAK plant construction time	24–36 months	30–48 months (four modules)	1 month	24 months
Proportion of construction work onsite	40%	—	100% factory assembled; onsite installation in <30 days	10%
Frequency of refueling and scheduled maintenance outages	12–42 months	Online refueling	8–20 years	48 months
Average duration of refueling and scheduled maintenance outages	10–25 days	N/A	—	30 days
Maturity level of the design	Expected deployment within 10 years	Expected deployment within 10 years	Expected deployment within 10 years	Expected deployment within 20 years
Ramping up capability	3%/min	—	—	—
Ramping down capability	10%/min	100–40–100% in 20 minutes; 100–25–100% at 5%/min	High-speed load following capacity	40–100%; 5–10%/min
Minimum allowable power output	—	—	—	40%

Characteristic	Light-Water SMR	High-Temperature Gas-Cooled SMR	Microreactor	SMR Utilizing Thorium fuel
CapEx	Estimated between $2,250–3,600/kWe	Estimated between $2,000–8,000/kWe	Estimated between $10,000–20,000/kWe	Estimated $1,000/kWe
Infrastructure for spent fuel	Spent fuel pool (storage length depends on design)	—	No onsite spent fuel or waste storage	Spent fuel pool or stored in the haul for plant life
Hybrid or dry cooling designs	Yes (optional)	Yes	No	No
Technically achievable emergency planning zone	Site boundary	0.4 km	—	0.5 km or plant boundary
Siting requirements considering enhanced resistance to geological risks	SSE: 0.3–0.5	0.5g seismic design	IBC Zone 4 Category F seismic design	SSE: 1
Citations	IAEA 2020; Black, Shropshire et al. 2021; NuScale 2022; U.S. NRC 2022; Holdman 2021	IAEA 2020; Thorium Energy World n.d.; Brits, Botha et al. 2018; Nuclear Innovation Alliance 2021; U.S. NRC 2022; Mignacca and Locatelli 2020	IAEA 2020; U.S. NRC 2022; Nichol and Desai 2019; Westinghouse 2022; Wald 2020	IAEA 2020; ThorCon 2022; U.S. NRC 2022

2.2 Outcome 2: Gather Data and Tools to Assess the Economics of Small Modular Reactor Designs

Increasing governmental, public, and private sector concern regarding climate change has resulted in commitments for carbon emission reductions around the world. In the commercial energy generation sector, a historical reliance on carbon-intensive energy generation technologies complicates this transition because fossil-fuel-based generation assets must be replaced without endangering grid reliability or creating significant financial burdens for end users. Because many utilities are induced to decarbonize either from external or internal commitments, generation mixes must be found that solve the often-conflicting goals of low cost, high reliability, accessibility, and carbon neutrality. Figure 2 shows these goals, which will be referred to as ECR, (environment, cost, reliability), for succinctness.

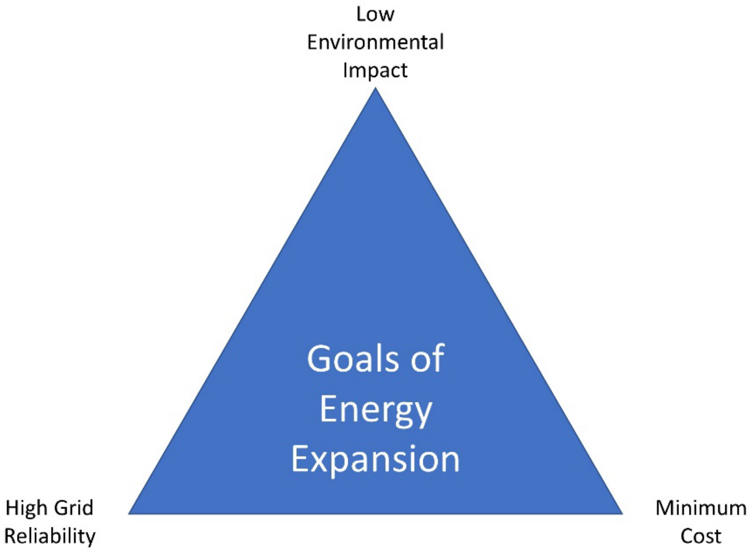

Figure 2. The often-conflicting goals of energy expansion.

Brazil's 2031 Ten-Year Energy Expansion Plan (EPE 2022) seeks to meet each of these goals simultaneously by utilizing technologies and applications, including variable renewable energy (VRE), distributed generation, demand response, and energy storage (EPE 2022). These considerations fall under the paradigm of energy capacity expansion—as Brazil's economy and thus energy demand is expected to increase in the future. The plan outlines the methods through which the Brazilian government can influence decision-making in the energy sector, both for governmental agencies and the private sector. In addition to the ECR goals, the 10-Year Plan also aims towards an increase in investment, industry participation, energy efficiency, and increased electrification.

The energy sources considered to meet these goals include solar thermal energy, photovoltaic solar, biomass thermal, biogas, wind, and hydro, among others. In addition, the plan contains several more carbon-intensive energy generation technologies, including coal and natural gas, whose expansion are proposed to be limited to reduce increases in grid carbon intensity. Brazil has unique considerations regarding its energy needs—including the fact that hydropower (the majority generation source in the country) might become less reliable due to recurrent droughts and environmental constraints on the flexible generation of plants with large reservoirs. Furthermore, environmental barriers to the construction of additional large hydropower plants hinder Brazil's potential utilization.

As stated previously, each of the ECR goals make the other two more difficult to achieve. High VRE penetration can have a low environmental impact but can reduce grid reliability and result in increased costs due to the necessity of excess capacity and energy storage. Minimum cost technologies are often carbon-intensive; although, the cost of VREs has reduced substantially over the past decades. Dispatchable generation technologies support grid reliability, but many dispatchable technologies are carbon intensive. The often-conflicting nature of ECR goals leads to a complex problem. Because there are typically no clear best solutions, decision makers are forced to determine the relative importance of each goal to arrive at what is perceived as the best result.

Nuclear technologies, including SMRs and MRs, stand out as technologies that may have the potential to meet each of the ECR goals simultaneously. Nuclear technologies are operationally carbon neutral and have a high reliability and capacity factor. Although there is little construction and operation experience with the technology, multiple vendor cost estimates are cost competitive with current energy generation technologies. This is expected for the Brazilian market as well. Nonfinancial considerations like carbon neutrality and high reliability can also factor into decision-making. SMRs and MRs can also help meet the goal of distributed energy generation, providing baseload power to smaller grids or energy users farther away from large municipalities.

There is little to no construction and operational experience with SMRs and MRs, meaning that cost estimates may not accurately reflect final costs. Nuclear waste management is still a difficult subject, but Brazil currently meets the radioactive waste recommendations of the IAEA (Heilbron et al. 2014). Public perception can also limit nuclear expansion, especially after nuclear disasters such as Fukushima and Three Mile Island. Despite these concerns, the potential of nuclear power to meet each of the ECR goals simultaneously warrants a review of the applicability of the technology to the Brazilian grid.

2.2.1 Small Modular Reactor Cost Data Summary

2.2.1.1 Small Modular Reactor Technology Overview

SMRs are nuclear reactors with typical operating capacities between 20 and 300 MWe. Reactors under 20 MWe are microreactors and those above 300 MWe are commonly referred to as LRs. This section provides an overview of SMR technology. Because of the uniqueness of each reactor concept, it may not be appropriate to directly compare one concept to another. However, concept data are presented side by side for ease of reading.

2.2.1.2 Comparison to Traditional-Scale Nuclear Power Plant

SMRs designs are unique from traditional-scale nuclear reactors in their design, construction, and operation. SMRs are expected to be factory fabricated and transported to the site, lowering the amount of onsite construction. These reactors are also designed to be modular, allowing for incremental capacity growth to meet demand. Factory fabrication is intended to increase the economies of learning and reduce construction time, leading the expectation that these designs will be cost competitive against alternative technologies. Other unique SMR characteristics include higher plant efficiencies, longer refueling cycles, reduced staffing needs, enhanced safety features, smaller emergency planning zones (EPZs), and the ability to work as a part of an integrated energy system. For a more in-depth discussion on the difference between traditional-scale reactors and SMRs, see Appendix A.

Traditional water-cooled (Gen III+) and innovative reactor technologies (Gen IV) SMRs share many characteristics. However, due to manufacturing and operational experience, water-cooled SMRs are the primary concepts that will immediately benefit from well-established regulatory requirements, risk profiles, and supply chains. Part of the uncertainty around prices can be attributed to untested Gen IV reactor use, even at a large reactor scale. However, both Gen III+ and Gen IV SMR technologies can benefit from 60 years of lessons learned from LRs on aspects such as vulnerability, accident, unlikely events, and accident consequence mitigation.

2.2.1.3 Inherent Uncertainty

Some uncertainty remains around both SMR designs and costs. Without historical data, cost estimates sometimes rely on data from LWRs characteristics to estimate SMR costs (top-down estimation) while considering how differences in SMRs and LRs are expected to impact cost. The alternative method is a bottom-up cost estimation, where estimates of actual material and labor requirements are summed to generate a final cost. While cost estimates are an important component of decision-making, it is important for investors to acknowledge the cost uncertainties currently.

2.2.1.4 Cost Parameters by Coolant Type

Table 4 presents a compilation of values or ranges for SMR and MR characteristics sourced from both literature and vendor data. The table details 13 parameters grouped by SMR coolant type: water, gas, and molten salt. The table also includes a column detailing the 13 parameters for heat-pipe microreactors. As shown in Table 1, data was not available for all parameters for all coolant types.

Both the thermal and electric capacity ranges are reported by reactor family. As shown in Table 4, available SMR data captures a wide range of both thermal and electric capacities. Nuclear reactors are thermal power plants, meaning heat is the initial product that can be converted to electricity, if desired. Some plants are utilized as combined heat and power plants, which can flexibly generate a mixture of heat and electricity in response to external conditions. In Gen III+ reactor technology, heat is generated in the form of steam. The amount of thermal power generated is the thermal capacity of the nuclear power plant (NPP). The amount of electric power left over after conversion (and in-house energy consumption) is the plant's gross electric capacity. The ratio between thermal and electric capacity generated is referred to as plant efficiency. For example, available information on gas-cooled SMRs report expected plant efficiencies of 43–53%, depending on the design. A plant efficiency of 43% means that only 43% of the thermal power generated will be converted into electric power. The other 57% will be lost in the conversion process. As can be seen in Table 1, some SMR vendors and literature report higher plant efficiencies than large-scale water-cooled reactors, which generally have plant efficiency between 30–33%.

Many cost estimations by vendors are overnight capital costs for Nth of a Kind (NOAK) SMRs.

The ranges in Table 4 capture the values reported by both literature and vendor estimates. The values and ranges presented below are based on the latest referenceable data; however, as concepts are continuously evolving, more recent results may not yet be published. As can be seen in the table, many of the ranges are quite large. This supports the inherent uncertainty around SMR costs and designs discussed above.

Table 4. Selected characteristics by SMR reactor type.

		SMR Parameter Ranges by Coolant Type			Heat-Pipe Microreactor
Reactor Type (by coolant)		Water	Gas	Molten Salt	Heat Pipe
Parameter	Thermal Capacity (MWth)	250–870	200–625	125–750	Unknown
	Gross Electric Capacity (MWe)	77–300	100–300	100–515	1 kWe–15 MWe
	Plant Efficiency (%)	In progress	43–53	42–66	6.7–40
	Plant Design Life (years)	40–80	60–80	60–80	10–40
	Fuel Cycle Length (months)	12–36	18–360–Continuous	Continuous–84	Continuous–180
	Plant Footprint (m^2)	4,877–90,000	10,000–62,5000	11,658–22,500	100–4000
	Site Footprint (m^2)	26,300–140,000	85,000–200,000	59,490–250,000	Unknown
	EPZ (unit)	Site boundary	<1 km radius	1/2 plant boundary	<0.5 acres
	Construction Time (NOAK, months)	24–36	24–42	24–48	1 month for onsite portion
	Target First-Of-A-Kind (FOAK)—Overnight Capital Cost ($/kWe)	$5,100–10,000	In progress	In progress	Unknown

	Target NOAK—Overnight Capital Cost ($/kWe)	$2,250–7,000	$1,900–4,500	$800–5,100	Unknown
	Target LCOE ($/MWh)	$40.0–65.0	$66.0	<$50.0	Unknown
	Earliest Expected First Use (year)	Mid-2020s	2028	2025+	Mid-2020s +
	* Authors' note: The ranges and values presented in this table are sourced from the individual citations in Tables 5–8 unless another source is provided.				(Yan et al., 2020)

2.2.2 Literature and Vendor Data on Small Modular Reactor Costs

This section presents SMR literature alongside specific vendor concepts' financial and technical characteristics. This paper does not provide an exhaustive list of vendor designs, choosing instead to present designs based on the availability of public data. The IAEA collects information on SMR concepts under development worldwide in their ARIS database (by design) (IAEA 2020) and compiles their findings in an annual report (IAEA Division of Nuclear Power 2020).

2.2.2.1 Literature

This subsection briefly discusses the publicly available literature on SMR costs. Refer to Appendix B for a more in-depth summary of each source gathered to support this work.

Literature on SMR costs is varied in the focus and estimation approach. As incipient technologies, without any long-term, real-world cost data to leverage, many papers aim to contribute to developing a standardized methodology to estimate SMR costs. Some such literature, such as Vegel and Quinn (2017), Stewart and Shirvan (2022), and Black, Aydogan, and Koerner (2021), choose to utilize a bottom-up cost estimation strategy. Other literature aiming to contribute to developing a standardized SMR cost estimation methodology, such as Boarin et al. (2021), Abdulla, Azevedo, and Morgan (2013), and Carelli et al. (2010), are more varied in their focus, methods, and considerations. Other literature on SMR costs focus on the competitiveness of SMRs across different markets and deployment scenarios. For example, Weimar et al. (2021), Black et al. (2021), and SMR Start (2021), examines the competitiveness of SMRs across U.S. and international markets, considering potential advantages and challenges of the technology. Boarin and Rictotti (2009), on the other hand, compared the financial competitiveness of SMRs in differing deployment scenarios compared to traditional large-scale reactors.

Other studies in the SMR cost literature focus on analyzing the economic impacts of SMR construction and operation. Studies that contribute to this focus area include the ScottMadden Management Consultants 2021 and Black and Peterson 2019 reports. The 2021 ScottMadden Management Consultants report examines the economic impacts of retiring coal plants and the potential for SMRs to create a just transition for the historically coal-supported communities. Black and Peterson (2019), however, specifically examined the economic impacts of siting an SMR at the INL site in Butte County, Idaho, in both the construction and operation phases.

Other SMR cost literature explores the financial risks of investing in different sized SMRs. By analyzing stochastic factors, such as capacity factor, overnight construction cost, and fuel cycle unit cost, Barenghi et al. (2012) examined how these factors impact risk across a timeline. The literature mentioned above is not an exhaustive list of studies examining the various topics related to SMR costs. Furthermore, the topics and focuses of the studies mentioned above are some of the many chosen focuses in this body of literature. The mentioned studies are not meant to comment on the quality of analysis or as a recommendation for a specific study. The previously mentioned literature is presented to provide an understanding of the types of questions researchers are attempting to tackle in this body of literature.

2.2.2.2 Small Modular Reactors by Coolant Types—Concepts

This section breaks down the data in Table 4 into specific design-by-design examples by coolant type. Example designs presented are for water-cooled, gas-cooled, and molten-salt SMRs, as well as for heat-pipe MRs. We present four to six example vendor concepts with their respective cost information for each coolant type. Water-cooled SMR designs are presented first, followed by gas-cooled and molten-salt designs. Lastly, we present vendor data for heat-pipe-cooled microreactors based on EPE's interest. The concepts presented are not to be taken as support or recommendation for specific designs. All the designs below are presented as representative designs and were chosen to highlight the range in possible parameter values and are sourced from publicly available data. It is unclear which designs presented in the following tables may be or become commercially available. However, a variety of designs presented allow a representative range of parameter values for EPE to consider.

Table 5. Example water-cooled vendor designs.

	Boiling Water Reactor X-300 (BWRX-300)	System-Integrated Modular Advanced Reactor (SMART)	NuScale Power Module (NPM)	SMR-160
Country	U.S./Japan	Korea/Saudi Arabia	U.S.	U.S.
Thermal Capacity	870 MWth (4)	330-365 MWth (2,4,5,6)	250 MWth (10)	525 MWth (4)
Gross Electric Capacity	270–290 MWe (2,4)	100–107 MWe (2,4,6)	77 MWe (10)	160 MWe (4,11)
Plant Design Life	60 years (2,4)	60 years (2,4,5,6)	40-60 years (2,4,9)	80 years (4,11)
Plant Efficiency	Unknown	30.3% (2)	Unknown	Unknown
Fuel Cycle Length	12–24 months (2,4)	36 months (4,5,6,8)	24 months (2)	24 months (4)
Plant Footprint	8,400 m^2 (2,4)	90,000 m^2 (4,6)	4,877 m^2 (2)	20,500 m^2 (4)
Site Footprint	26,300 m^2 (2)	Unknown	140,000 m^2 (2,4)	Unknown
EPZ	At site boundary (1 km) (2)	Unknown	At site boundary (2)	At site boundary (11)
Construction Time (NOAK)	24–36 months (1,2)	<36 months (7)	36 months (2,9)	24–30 months (4,11)
Target FOAK—Overnight Capital Costs	<$1B USD (2)	$1B USD/ $10,000/kWe (4,8)	$5,100/kWe (5)	Unknown
Target NOAK—Overnight Capital Costs	<$2,250/kWe (2,3)	$5,250–7,000/kWe (4,5)	$2,850–3,600/kWe (10)	Unknown
Target LCOE	Unknown	$60.0–62.0/MWh (2,5)	$40.0–65.0/MWh (9)	Unknown
Technology Readiness	2028 (1,3,4)	Unknown	2027 (4,10)	Mid-2020s (4)
Sources	(GE-HITACHI 2022) (1) (IAEA 2020) (2) (IAEA 2019) (3) (IAEA Division of Nuclear Power 2020) (4) (OECD 2016) (5)			

	Boiling Water Reactor X-300 (BWRX-300)	System-Integrated Modular Advanced Reactor (SMART)	NuScale Power Module (NPM)	SMR-160
	(SMART Power Co. Ltd. 2022) (6) (Kim et al. 2014) (7) (Mansouri 2019) (8) (NuScale 2022) (9) (NuScale 2020) (10) (Holtec International 2022) (11)			

Table 6. Example gas-cooled vendor designs.

	Energy Multiplier Module (EM2)	Prismatic Modular High-Temperature GCR (Prismatic HTR)	Stem Cycle High-Temperature Gas-cooled Reactor (SC-HGTR)	The 300 MW(e) Gas Turbine High-Temperature Reactor (GTHTR300)	XE-100
Country	U.S.	U.S.	U.S.	Japan	U.S.
Thermal Capacity	500 MWth (4)	350 MWth (1)	625 MWth (1,4)	<600 MWth (1,4,8)	200 MWth (4)
Gross Electric Capacity	265 MWe (2,4)	150 MWe (1)	272 MWe (1,4)	100–300 MWe (1,4,8)	80 MWe (9,10)
Plant Design Life	60 years (1,3,4)	60 years (1)	80 years (1,4)	60 years (1,4)	60 years (10)
Plant Efficiency	53% (1,3,4)	Unknown	43% (1)	45.6–50.4% (1,4,7)	42.3% (9)
Fuel Cycle Length	360 months (1,2,3,4)	18 months (1)	18–24 months (1)	18–48 months (1,4,5,8)	Online fuel loading (4,11)
Plant Footprint	10,000 m^2 (1)	Unknown	10,000 m^2 (1,4)	62,500 m^2 (4)	130,900 m^2 (four modules) (4)
Site Footprint	85,000 m^2 (1)	Unknown	200,000 m^2 (1)	Unknown	Unknown
EPZ	16 km (radius) (1)	Unknown	0.4 km (radius) (1)	Unknown	Unknown
Construction Time (NOAK)	42 months (1)	Unknown	24 months/module (1)	24–36 months (5)	30–48 months/ four modules (11)
Target FOAK—Overnight Capital Costs	Unknown	Unknown	Unknown	Unknown	Unknown
Target NOAK—Overnight Capital Costs	\$4,330–4,500/kWe (1,3)	Unknown	\$3,900/kWe (1)	~\$2,000/kWe (6,8)	Unknown
Target LCOE	\$66.0/MWh (1)	Unknown	Unknown	Unknown	<\$60.0/MWh (9)
Technology Readiness	2032 (1)	Unknown	2033 (4)	2030 (4)	2027 (9)

	Energy Multiplier Module (EM2)	Prismatic Modular High-Temperature GCR (Prismatic HTR)	Stem Cycle High-Temperature Gas-cooled Reactor (SC-HGTR)	The 300 MW(e) Gas Turbine High-Temperature Reactor (GTHTR300)	XE-100
Source(S)	(IAEA 2020) (1) (General Atomics 2022) (2) (Faibish 2018) (3) (IAEA Division of Nuclear Power 2020) (4) (Nishihara et al. 2018) (5) (Yan et al. 2002) (6) (Takei et al. 2006) (7) (Yan 2017) (8) (Mulder 2021) (9) (X-energy 2022) (10) (DOE Office of Nuclear Energy 2021) (11)				

Table 7. Example molten-salt vendor designs.

	Liquid Fluoride Thorium Reactor (LFTR)	Small Fluoride Salt-Cooled High-Temperature E Reactor (SMAHTR)	Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (MK1 PB-FHR)	ThorCon	Integral Molten Salt Reactor 400 (IMSR-400)	Stable Salt Reactor Wasteburner (SSR-W300)
Country	U.S.	U.S.	U.S.	U.S.	Canada/ U.S.	U.S.
Thermal Capacity	600 MWth (2)	125 MWth (1)	236 MWth (1,2)	557 MWth (2)	400–440 MWth (1,2)	750 MWth (2)
Gross Electric Capacity	250 MWe (2)	N/A	100 MWe (1,2)	250–258 MWe (2)	194 MWe (1)	300 MWe (2)
Plant Design Life	Unknown	60 years (1)	60 years (1,2)	80 years (1)	56–60 years (1,2)	60 years (2)
Plant Efficiency	45% (2)	N/A	42-66% (1)	46 % (2)	46-48% (1)	N/A
Fuel Cycle Length	Continuous (2)	6 months (1)	Online refueling (2)	48 months (1,2)	84 months (1)	Refueling at power (2)
Plant Footprint	Unknown	Unknown	45,000 (2)	11,658 m^2 (2)	45,000 m^2 (2)	22,500 m^2 (2)
Site Footprint	Unknown	Unknown	59,489 m^2 (3)	250,000 m^2 (1)	70,011 m^2 (5)	Unknown
EPZ	Unknown	Unknown	Unknown	0.5 (plant boundary) (1)	Unknown	Unknown
Construction Time (NOAK)	Unknown	Unknown	Unknown	24 months (1)	48 months (5)	Unknown

	Liquid Fluoride Thorium Reactor (LFTR)	Small Fluoride Salt-Cooled High-Temperature E Reactor (SMAHTR)	Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (MK1 PB-FHR)	ThorCon	Integral Molten Salt Reactor 400 (IMSR-400)	Stable Salt Reactor Wasteburner (SSR-W300)
Target FOAK—Overnight Capital Costs	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Target NOAK—Overnight Capital Costs	Unknown	Unknown	$4,500–5,100/kWe (3)	$800–1,000/ kWe (1,4)	Unknown	$2,115/kWe (6)
Target LCOE	Unknown	Unknown	Unknown	Unknown	<$50/MWh (5)	<$50/MWh (6)
Technology Readiness	Unknown	Unknown	Unknown	2026–2028 (2)	Early 2030s (5)	2026 (6)
Source(s)	(IAEA 2020) (1) (IAEA Division of Nuclear Power 2020) (2) (Andreades and Peterson 2015) (3) (ThorCon 2022) (4) (Terrestrial Energy 2022) (5) (Moltex Energy Canada Inc. 2017) (6)					

Table 8. Example heat-pipe microreactors.

	eVinci	MoveluX
Country	U.S.	Japan
Thermal Capacity	7–13 MWth (1,2)	10 MWth
Gross Electric Capacity	2–3.5 MWe (1,2)	3–4 MWe
Plant Design Life	40 years (1)	10–15 years
Plant Efficiency	Unknown	Unknown
Fuel Cycle Length	36–96 months (1,2)	Continuous
Plant Footprint	<4,000 m^2 (1)	100 m^2
Site Footprint	Unknown	Unknown
EPZ	<0.5 acres (3)	Unknown
Construction time (NOAK)	1 month (onsite portion) (2)	Unknown
Target FOAK—Overnight Capital Costs	Unknown	Unknown
Target NOAK—Overnight Capital Costs	Unknown	$4,000/kWe
Target LCOE	Unknown	Unknown
Technology Readiness	Mid-2020s (1)	2035
Source(s)	(IAEA 2020) (1) (Westinghouse 2022) (2)	(IAEA 2020)

	eVinci	MoveluX
	(BrucePower and Westinghouse 2021) (3)	

2.2.3 Brazil Macroeconomic Assessment Discussion

This section addresses the fifth technical area of the study to evaluate the broader, longer-term trade-offs for using reactors. As part of the overall SMR assessment, understanding the broader economic implications from the reactors at the local, regional, and national level is important, especially during the planning phase of the project. A macreoeconomc assessment performed by economists in Brazil can provide a top-down view of the the economic value of an SMR project as compared to other alternatives. This information is useful for conveying benefits of the project to stakeholders and decision makers that is necessary to gain project approval, secure financing and secure support from the public. This analysis extends the technical assessment of the technology by understanding the economic value, including jobs, taxes, and revenues, and possible societal benefits (e.g., pollution reduction, improved air quality).

This section can assist Brazil's EPE by providing the framework for performing a macroeconomic assessment that includes a high-level overview of the importance, history, and valid use cases of regional economic impact modeling, specifically utilizing the most widely applied methodology, input-output (I-O). A low-to-medium-technical level of methodology is presented, as well as literature review of sources and relevant data. Additional datasets will be required to perform a complete macroeconomic analysis, however whenever possible, examples, literature, and data specific to Brazil are utilized to increase relevancy for the target audience.

2.2.3.1 Introduction and Example Analysis

Regional[a] Economic Impact Analyses (R-EIA) is a collection of methods used to estimate the effect of a given project or policy on the economy of a defined region. Effects examined can include changes in economic activity (gross regional product), business profits, job creation or loss, prices, and more. These effects can be captured both generally and in detail, revealing overall effects and effects to specific industries or products. While this paper will focus on presenting I-O methodology, other methodologies will be briefly discussed.

R-EIA and I-O are both relatively young but maturing fields in macroeconomics. While a detailed history of the practice is outside of the scope of this paper, a discussion of the topic can be found in (Miller and Blair 2009). This methodology is generalizable to a large variety of project analyses. Practitioners can add or change the model's underlying assumptions and choose any relevant region, assuming the availability of requisite data. Even without complete data, I-O methodology can be utilized with the proper assumptions, which will be discussed later in this paper. However, results are generally more accurate the greater the detail of available data. The adaptability of the methodology allows researchers to conduct an analysis tailored specifically to the unique characteristics of the proposed project.

R-EIAs can be utilized as a complement to cost-benefit analyses (CBA), which compare the competitiveness (as defined by decision makers across any number of factors) of a project or policy to any number of others. These comparison cases can include a base case (business as usual) or other cases that satisfy the minimum requirements of the project needs.

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[a] Note that "Regional" in the context of this paper refers to any bounded geographic area—for example a country, state, county, province, or multicounty area. The region of analysis is defined by the researcher and should be relevant to the studied project.

2.2.3.2 Example Analysis

This paper will utilize an extended example to increase the relevance of the R-EIA methodology (specifically I-O analysis) discussion and results. Although Brazil and specific power plants are used as characteristics for this example, it is not intended as an analysis of a potential project. Note that although R-EIAs can evaluate the effects of either a project or policy, the remainder of this paper will only refer to analysis of projects, as they are the topic relevant to Brazil's case.

This paper uses the hypothetical replacement of the Porto do Itaqui (PDI) Coal Power Plant with a multiunit SMR system to support the explanation of I-O methodology. PDI is located in the northeastern state of Maranhão and has a capacity of 360 MWe. The plant provides roughly 40% of the state of Maranhão's total electricity consumption (Eneva n.d.). The energy transition is assumed to occur due to increasing international political pressure to replace carbon-intensive energy assets with carbon-neutral assets. Funding for the SMR plant is further assumed as a mixture of government and corporate investment. Because of the impact the project, if accepted, will have on Maranhão's economy, electricity market, and employment, an R-EIA is commissioned as a component of a larger CBA.

2.2.3.3 Importance of Regional Economic Impact Analyses

As stated previously, R-EIAs can provide robust quantitative estimations of a project's economic impacts. Primarily, these results can be used to determine whether a project will have a positive or negative impact and the magnitude of the impact on the economy. In addition, these results can be utilized by decision makers to promote a project should it have a positive impact on the region (for example, "this project is expected to create X number of jobs in the new nuclear industry and Y number of jobs in the metals fabrication industry"). These statistics can motivate the public and political spheres to support a project based on its benefit to the region. However, it is crucial for R-EIA analysts to remain impartial, avoiding funding or sponsorship bias.

Many projects with financial components and potential alternatives conduct CBA to determine the most competitive project based on decision-maker-defined criterium. Depending on the scale of the considered project, analyses may begin and end with a financial competitiveness evaluation or a Comparative Techno-Economic Assessment (C-TEA). Financial competitiveness evaluations compare the financial costs and benefits of a given project to determine which alternative is either the most profitable or least costly (or other goals prioritized by the decision maker), while C-TEAs include a significant analysis of technological capabilities and characteristics (in addition to the financial competitiveness evaluation). For example, C-TEAs can consider the physics underlying a nuclear system, including transfer rates, ramp rates, and physical system operation. R-EIAs fit under the umbrella of CBA, examining the costs and benefits of a project (or projects) to a region's economy, and can be considered an optional (but important) addition to a comprehensive CBA.

2.2.4 Regional Economic Impact Analyses General Methodology

This section presents a high-level nontechnical methodological overview followed by a more technical description. Finally, sources are presented which cover technical methodology at a high level of detail.

I-O analyses capture the impacts to a region's economy created by an exogenous shock and then the shock's subsequent effects through *industry interrelationships* and relationships with *government*, *households*, and *foreign markets*. In most use cases, I-O models only examine impacts projects have within an economy and do not model any changes to the underlying economy of the region. Additionally, models utilize the economic conditions of a region at a given moment in time. As such and without extensions, I-O models are considered static models (Watson 2019).

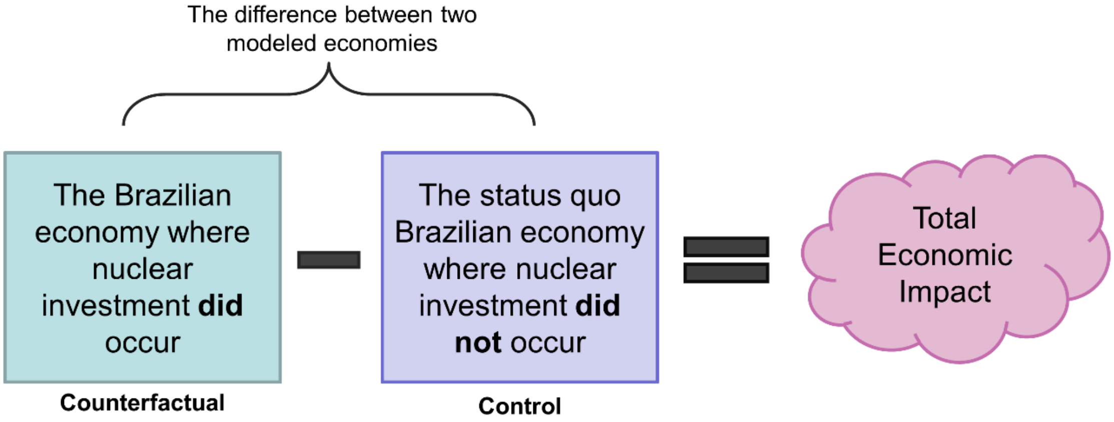


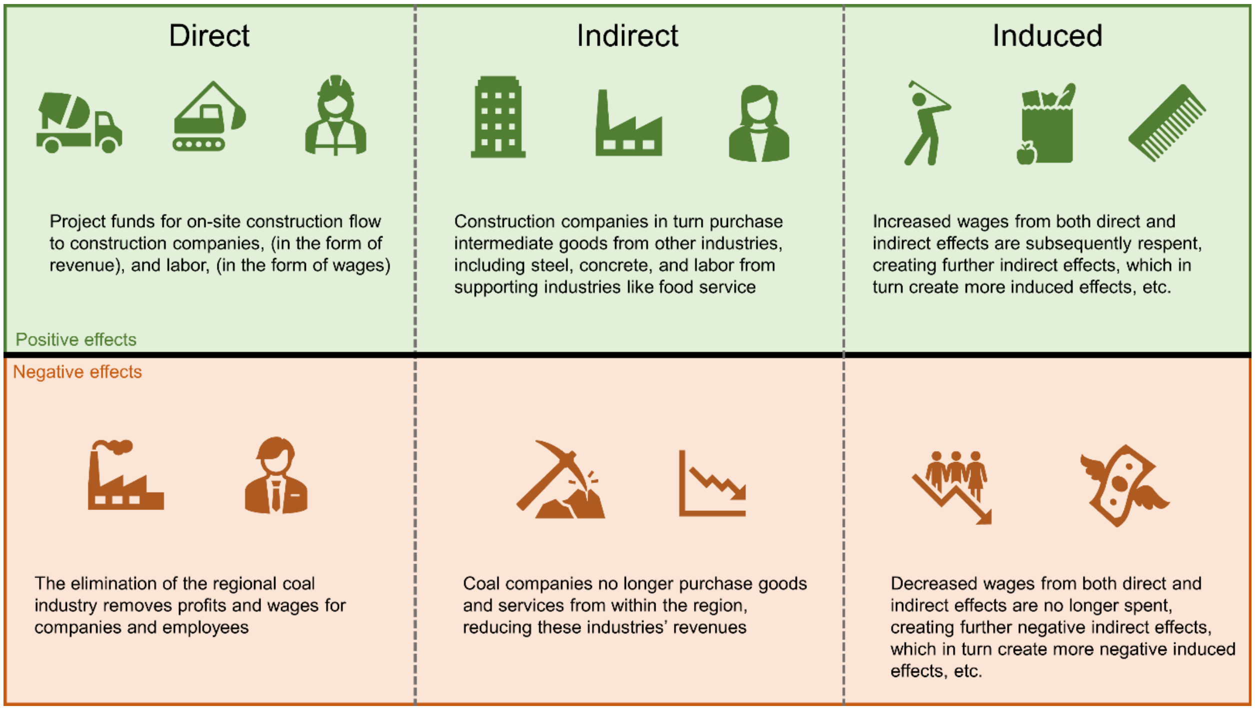
Figure 3. Explanation of control and counterfactual.

Figure 3 shows a representation of R-EIA, which is simply the comparison between a counterfactual (the situation where a project **did** occur) and a control (the base case or business-as-usual case where a project **did not** occur—the current economy). These cases can be quantified in many ways, including effects on employment, gross regional domestic product (a measure of a the size of a region's economy), and household income. Multiple metrics can be utilized, and the relative importance of these metrics can be determined by decision makers.

Exogenous shocks can have both positive and negative impacts on a regional economy. For example, replacing a coal-fired power plant with an SMR will reduce coal-oriented employment while adding nuclear jobs. Whether the project has a *net* positive or negative impact is determined by the relative magnitude of each effect. Projects can have mixed effects across economic metrics—for example, creating jobs while decreasing gross regional domestic product.

2.2.4.1 Effects and Interrelationships

R-EIAs estimate three types of effects, *direct*, *indirect*, and *induced*, which will be discussed in this section. Additionally, a discussion of the multiplier effect and leakage is presented.



Project funds for on-site construction flow to construction companies, (in the form of revenue), and labor, (in the form of wages)

Construction companies in turn purchase intermediate goods from other industries, including steel, concrete, and labor from supporting industries like food service

Increased wages from both direct and indirect effects are subsequently respent, creating further indirect effects, which in turn create more induced effects, etc.

The elimination of the regional coal industry removes profits and wages for companies and employees

Coal companies no longer purchase goods and services from within the region, reducing these industries' revenues

Decreased wages from both direct and indirect effects are no longer spent, creating further negative indirect effects, which in turn create more negative induced effects, etc.

Figure 4. Depiction of economic effects of a nuclear project.

Figure 4 shows example direct, indirect, and induced effects relevant to the hypothetical case at PDI. Direct effects are a single round of effect, only the initial project spending received as revenues by regional industries. Indirect and induced effects impact the economy through multiple rounds of spending. The following sections describe these effects in more detail.

Figure 5 presents a simplified circular economy model, displaying how money from projects enters an economy and subsequently cycles through the economy multiple times. This spending can magnify both positive and negative effects, leading to situations where the overall impact of a project is far larger than the initial spending. The diagram is simplified to reflect the economic interrelationships most relevant to the hypothetical PDI case.

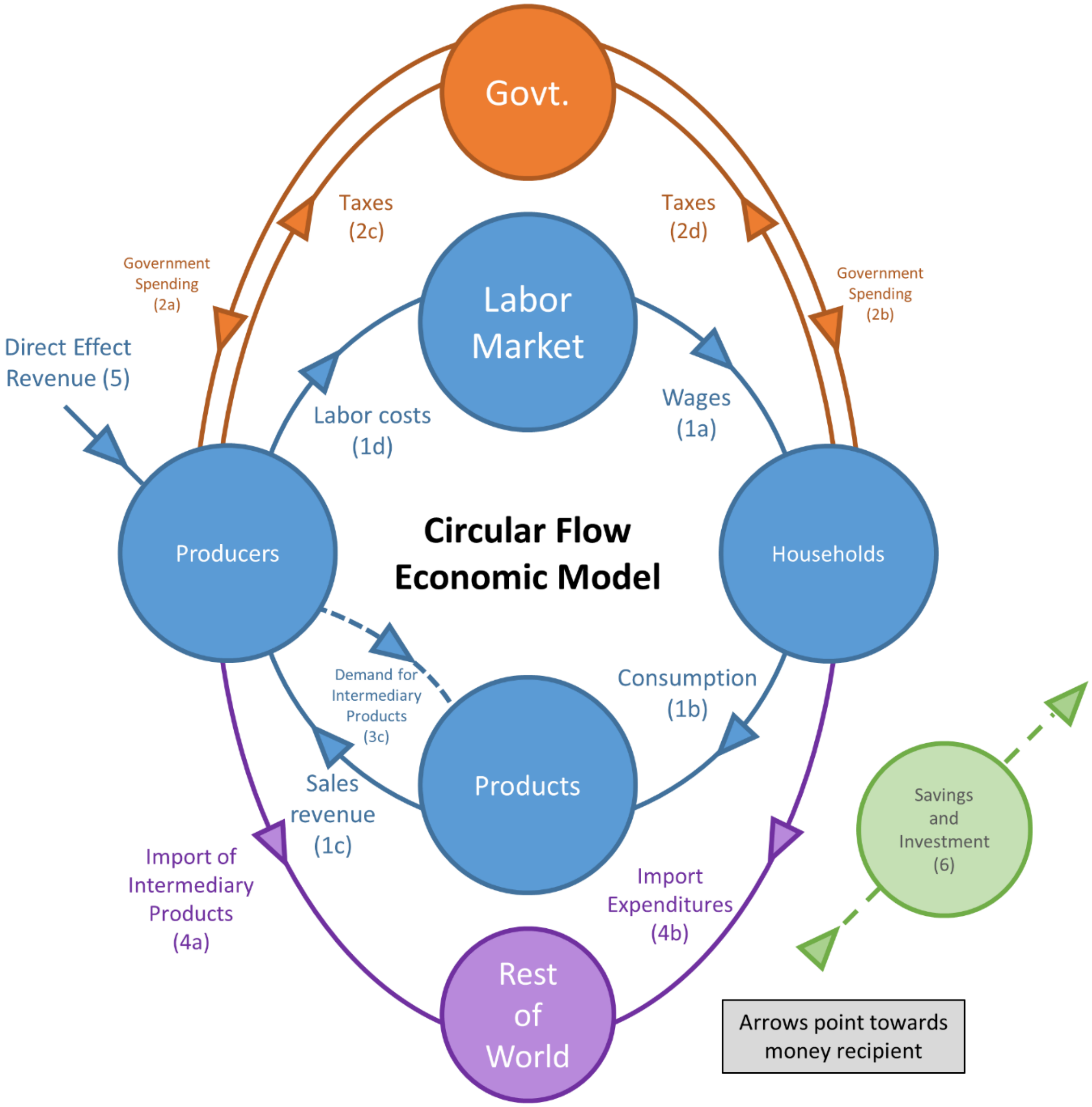


Figure 5. Circular flow model for effects of nuclear projects.

2.2.4.2 Initial Shock (Direct Effect)

To continue with the PDI replacement example, the initial shock is spending associated with the construction of a multiunit SMR and any other immediate spending (fabrication, labor costs, etc.). This money flows to producers (in the form of revenues) and then to households (in the form of wages). In Figure 5, the Producer bubble is immediately impacted by direct effects (Line 5), and some employees receive additional wages from the direct effects (Arcs 1d and 1a). These dollars are associated with certain industries—for example, onsite construction activities would be classified under the construction industry. Additional methodological considerations and assumptions must be made when a new industry is being created—for example, a new nuclear industry must be created within the I-O matrices because there currently is no nuclear industry in Maranhao. It is important to note that only the dollars spent within the studied region must be considered—all other spending is considered a leakage and does not impact the region's economy. For example, if a reactor is produced in Canada and shipped to Maranhao, fabrication would not be considered in the R-EIA. However, construction activities onsite would be considered.

It is also important to recognize that effects can be positive for some industries while negative for others—a fact that will be explored in more depth later in this section. While each of the following sections discuss increases in revenues to regional businesses and wages to regional employees, the inverse is also possible.

2.2.4.3 Indirect Effects

As shown above, regional industries receive new dollars from direct effects, which are subsequently used to purchase *industry inputs*: the intermediate goods and services represented by Arc 3c. Spending within the region is part of the indirect effect—industries that do not receive direct revenue from the project but instead receive spending from the direct effect industries. Money spent outside the region is considered leakage and is no longer considered.

Continuing with the PDI example, a portion of the construction industry's new revenue is used to purchase concrete and rebar. This subsequent round of spending is categorized as indirect effects. To take the example further, rebar manufacturing companies must purchase steel as an intermediate good, which is another round of indirect effects. Project dollars are thus spent through the economy many times in accordance with each industry's interrelationship with every other industry. Because leakage occurs at every round, the total effect of each subsequent round is smaller than the round that precedes it. Note that economies with a more tightly enmeshed regional economy (producers purchase relatively more intermediate goods from other regional industries as opposed to imports from outside the region) will generally experience a larger magnitude of economic effects given that the leakage is slower.

2.2.4.4 Induced Effects

As directly and indirectly impacted industries receive more revenue because of the examined project, they pass a portion of the additional money to employees in the form of wages. In turn, employees spend these new wages on goods and services (Arc 1b) or savings (Circle 6), both in and out of the region. These effects are captured by household consumption of goods and services (Arcs 1b and 1c). For example, this consumption could include spending on groceries, recreational activities, and haircuts. Household spending is then captured by these industries as revenue, which is in turn passed through wages to households, which is then respent as household consumption, etc. During each round of respending, a portion of the money leaks out of the region and is no longer considered within the R-EIA. This means that the relative effect of each round of respending is smaller than the last until the effects are negligible. I-O modeling captures the sum of these effects and determines the amount of impact generated by each industry.

2.2.4.5 Multiplier Effects

The combined round-by-round spending of the direct, indirect, and induced effects for each industry is that industry's multiplier and are derived from the I-O table and matrix. A more diversified and integrated economy will have higher industry multipliers and less leakage (imports). A higher multiplier represents a larger effect, while a lower multiplier represents the opposite. To use employment as an example, a multiplier of 1.25 within an industry shows that an initial increase in one job results in the creation of 0.25 additional jobs. Similarly, a multiplier of 2.3 represents the creation of 1.3 additional jobs beyond the initial job. If one job is directly lost in an industry with a multiplier of 2.3, then 1.3 additional jobs will also be lost. These additional jobs are created and lost by indirect and induced effects, which are explored above. Analysts conducting I-O analyses can refer to more supporting sources on the multiplier effect in Appendix B.

Figure 6 helps demonstrate the multiplier effect. The left side of the figure shows the round-by-round spending. As can be seen below, in each subsequent round some part of the initial dollar is then spent again locally and the rest leaves the studied region (leaks out). This goes on until what remains is negligible. The right side of the figure demonstrates that the sum of all the rounds of spending equals the multiplier effect.

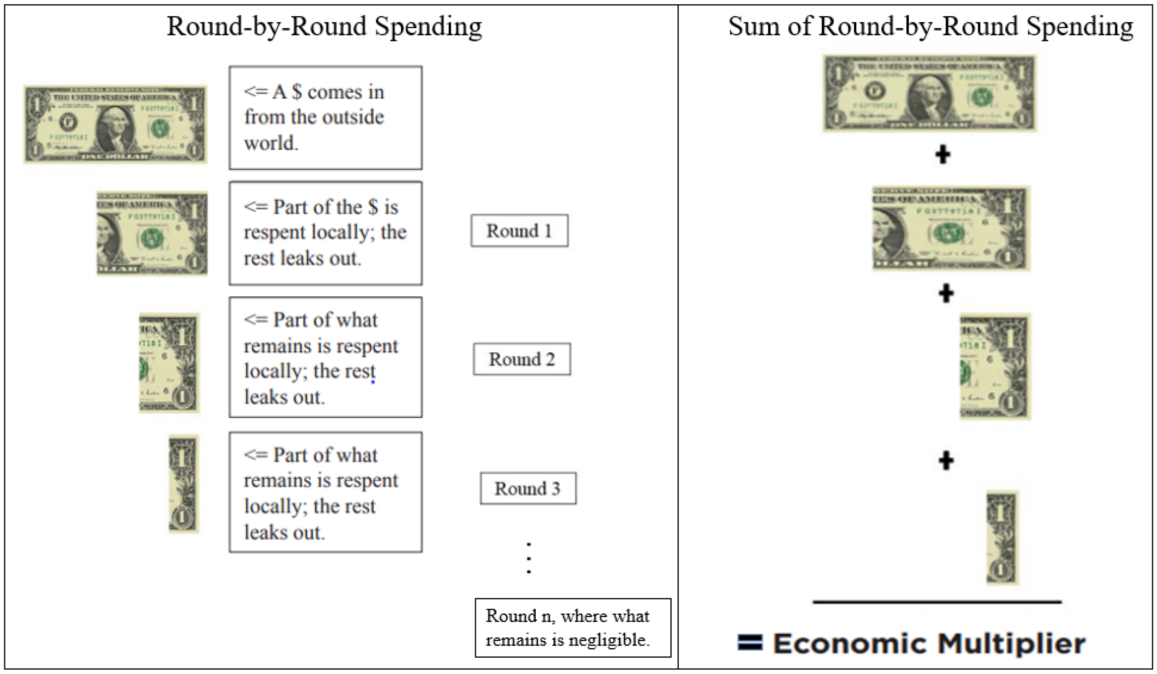


Figure 6. Adapted from (Hughes 2018).

Multiplier effects generally fall within four categories, the increases or decreases in:

1. Sectoral output—value of outputs sold to other sectors, including households
2. Household income—wages received by individuals which are then spent or saved
3. Employment—job numbers within each industry
4. Value added—unit profits less unit production costs.

2.2.4.6 Government

Governments tax both producers (business taxes) and households (income taxes). However, governments also spend money through a variety of methods that benefit both producers and households. If the effects of the nuclear project increase business revenues and household income, total government tax revenue will increase. A portion of this additional tax revenue will then be spent by the government and injected back into the economy. Like other spending within the economy, government spending creates additional rounds of effects with leakage at every round. These effects are also captured by I-O analyses and are included in the total effects.

2.2.4.7 Rest of the World

The rest of the world is considered primarily (at least in the case of a Brazilian nuclear project) for leakage effects as money is spent outside the region. This spending on imports is not restricted to imports from outside the country—any purchase from outside the study region is an import and exits consideration from the R-EIA. Producers (Arc 4a), households (Arc 4b), and governments (not shown) spend outside the study region, creating leakage in each subsequent round of spending. The other relationship between the region and the rest of the world is exports, which bring new money to the region. While the nuclear project itself may not generate significant, if any, exports, the increased revenues to regional businesses may increase exports and thus money flowing into the region. Like other financial effects, these new dollars are spent and respent within the economy until effects are negligible.

2.2.4.8 Savings and Investment

Each actor in the model also interacts with savings and investment markets (Line 6). Financial markets facilitate interactions between savers and borrowers—in traditional economic theory, whatever households and producers do not spend on goods and services is either saved or invested. These actions further contribute to economic effects as savings are loaned and investments are utilized by the companies being invested in. This topic is outside the scope of this paper but is discussed in (MacIntosh and O’Gorman 2015).

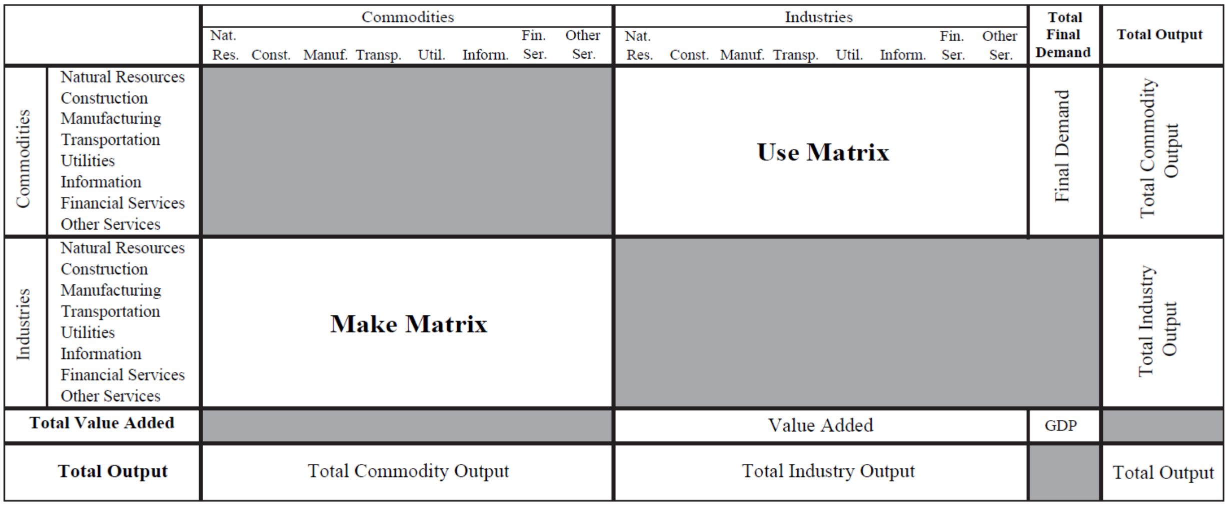
2.2.5 Data Required

R-EIAs are large, rigorous studies that require a significant amount of data. Gathering, assembling, and modifying the data to meet the needs of the study while maintaining accuracy is often the most time-consuming stage of a study. Miller and Blair’s work (2009) can be considered the comprehensive guidebook to R-EIAs—as such, it will be summarized here alongside other key readings.

Matrices capturing economic statistics and relationships are required to estimate the direct, indirect, and induced effects of a project. As stated by Miller and Blair (2009), “the existence of a statistically robust data source for precisely the geographic area under consideration, for precisely the time period of interest, and for precisely the level of sectoral detail of interest is both the most desirable and the least likely situation.” As such, several steps are required to adjust existing data into a format that is usable in I-O analyses. The following sections describe these steps and data products.

2.2.5.1 Input-Output Accounts

Input-output accounts capture interindustry and intersector relationships, primarily between producers, households, governments, and the rest of the world. The table captures both intermediate and final demands, revealing, for example, how industries purchase from one another, what goods are imported and exported, and how industries and households are taxed by the government.



		Commodities	Industries	Total Final Demand	Total Output
		Nat. Res. Const. Manuf. Transp. Util. Inform. Fin. Ser. Other Ser.	Nat. Res. Const. Manuf. Transp. Util. Inform. Fin. Ser. Other Ser.		
Commodities	Natural Resources Construction Manufacturing Transportation Utilities Information Financial Services Other Services		**Use Matrix**	Final Demand	Total Commodity Output
Industries	Natural Resources Construction Manufacturing Transportation Utilities Information Financial Services Other Services	**Make Matrix**			Total Industry Output
Total Value Added			Value Added	GDP	
Total Output		Total Commodity Output	Total Industry Output		Total Output

Figure 7. Commodity by industry make and use table. Source: (Miller and Blair 2009).

Figure 7 provides a condensed version of a symmetric industry-by-industry I-O table. In the table, the Make Matrix represents the amount commodities generated by each industry (expressed in monetary terms), while the Use Matrix represents the consumption of commodities by industries as intermediary inputs towards the production of other intermediary inputs or final goods. Commodity rows culminate in both the final demand and total commodity output columns. Industry rows culminate to show total industry output.

In the matrix, rows represent the production of commodities or industries. The production of each row header is split up by column to represent how much of the commodity's or industry's output is consumed either by an industry or in the production of final goods. For example, the commodities within the manufacturing row or the manufacturing row within the industries header connect with the construction industry based on the construction purchase of intermediate goods from the manufacturing industry. The final goods column is any goods or services purchased that are not utilized in the production of another good.

2.2.6 Available Data for Brazil

There are two primary data sources for Brazil examined in this paper, one sourced from (OECD.Stat 2018) and the other from (Instituto Brasileiro de Geografia e Estatística 2015).

2.2.6.1 OECD.Stat

OECD.Stat hosts economic data for many countries, including Brazil. The 2018 dataset for Brazil contains the following matrices. Note that the tables are condensed for space and only include a sample of rows and columns:

Total

The total matrix shows the value of production sent from producers to either intermediate or final demands. For example, Brazil's agriculture, forestry, and fishing industry (henceforth referred to as agriculture) produces approximately $6.1 billion (2015 USD) used as intermediate goods for further production in the agriculture industry. The agriculture industry also produces approximately $23 million of intermediate goods for Brazil's energy-producing mining industry. Finally, agriculture has a cross-border export total of $34.3 billion. These values give an initial view of each industry's size and the interindustry relationships present in the economy. Note that this table is an industry-by-industry table that does not discuss specific commodities, a difference from Table 10.

Table 9. Industry-by-industry total matrix.

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products	Direct purchases abroad by residents (imports)	Direct purchases by non-residents (exports)	Exports (cross border)	Imports (cross border)
Agriculture, forestry, and fishing	6,071.2	22.9	12.6	150.2	17.4	34,291.8	3,343.4
Mining and extraction of energy-producing products	35.2	3,165.2	72.9	6.4	0.2	11,513.1	13,509.9
Mining and quarrying of non-energy-producing products	148.4	134.8	774.1	1.1	—	15,903.2	2,324.1
Mining support service activities	390.2	1,981.2	412.9	0.2	—	62.1	73.5
Food products, beverages, and tobacco	4,743.3	149.8	51.6	583.8	53.8	30,575.3	7,327.9

Domestic Output and Imports

The domestic output and imports matrix shows “the supply of goods and their use by product groups and homogeneous branches, which are delimited in a uniform manner in the rows and columns, or by final uses categories i.e., exports” (OECD 2006).

Table 10. Domestic output and imports matrix.

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products	Direct purchases by non-residents (exports)	Exports (cross border)
Agriculture, forestry, and fishing	5,915.9	7.8	9.2	17.4	34,291.8
Mining and extraction of energy-producing products	18.0	2,277.1	43.7	0.2	11,513.1
Mining and quarrying of non-energy-producing products	131.5	120.4	673.3	—	15,903.2

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products	Direct purchases by non-residents (exports)	Exports (cross border)
Value added at basic prices	77,943.7	20,263.3	11,020.3	—	—
Output at basic prices	145,972.1	47,609.5	26,401.3	—	—

Value Added

"Value added reflects the value generated by producing goods and services and is measured as the value of output minus the value of intermediate consumption. Value added also represents the income available for the contributions of labor and capital to the production process" (OECD 2021).

Table 11. Value added.

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products
Compensation of employees	14,991.8	6,436.7	2,569.9
Other taxes less subsidies on production	(2,718.1)	318.7	177.2
Gross operating surplus and mixed income	65,670.1	13,508.0	8,273.2

Leontief Inverse Matrix (Total)

The total Leontief inverse matrix is the representation of the final effects of a project on the economy. For example, for every dollar of direct impact to the agriculture sector, $1.06 of impact is eventually created.

Table 12. Total Leontief inverse matrix.

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products
Agriculture, forestry, and fishing	1.06	0.01	0.01
Mining and extraction of energy-producing products	0.04	1.10	0.05
Mining and quarrying of non-energy-producing products	0.01	0.01	1.04
Total	1.97	2.07	2.14

Leontief Inverse Matrix (Domestic)

The domestic Leontief inverse matrix is similar to the total matrix but captures effects directly attributable to the domestic sector.

Table 13. Domestic Leontief inverse matrix.

From: Sectors in rows To: Sectors in columns (Millions of USD, 2015)	Agriculture, forestry, and fishing	Mining and extraction of energy-producing products	Mining and quarrying of non-energy-producing products
Agriculture, forestry, and fishing	1.1	0.0	0.0
Mining and extraction of energy-producing products	0.0	1.1	0.0
Mining and quarrying of non-energy-producing products	0.0	0.0	1.0
Total	1.7	1.7	1.9

Imports Content of Exports, As a Percent of Exports

This matrix shows what percentage of exports are imports. For example, energy-producing mining product exports are 16.6% imports. This metric gives one aspect of leakage.

Table 14. Imports content of exports.

From: Sectors in rows To: Sectors in columns (Percent)	Import content of exports shares
Agriculture, forestry and fishing	0.0967
Mining and extraction of energy-producing products	0.1658
Mining and quarrying of non-energy-producing products	0.1246
Total	12.56

2.2.7 Discussion and Conclusion

This section discusses the importance of Economic Impact Assessments (EIA) and provides helpful sources and information to assist researchers conducting a full analysis in the Brazilian context. EIAs support decision makers in understanding the effects a project will have on a region. This section does not attempt to complete an EIA but instead introduces the I-O methodology, explaining key terminology and concepts and presenting example Brazilian data sources.

In order to carry out an EIA for SMR deployment in Brazil, researchers must determine the scale of analysis and SMR design. A decision on the scale of analysis is required to determine the economic region, which in turn defines the rest of world region. For example, if the Brazilians are interested in the impacts of siting an SMR on the São Paulo state economy, the rest of the world becomes all the other states in Brazil and other countries. Any part of the initial money spent outside of São Paulo is therefore not included in the multiplier effect. To know the size of the initial shock, researchers would need to use cost data from a specific vendor or from public literature. SMR plant staffing information and regional workforce statistics are also important to carry out an EIA.

Next steps for Brazilian researchers include gathering more localized data, constructing full I-O matrices, and selecting specific SMR or MR cost values for use in the analysis. Universities and governmental statical offices may have prior experience conducting this type of analysis and therefore may be a valuable resource to leverage.

2.3 Outcome 3: Identify and Assess Technical Implications from Small Modular Reactor (Generic) Applications for Brazil

2.3.1 Introduction

SMRs and microreactors (MRs) are incipient technologies. As such, there is little experiential data available to provide insight into which market environments these nuclear technologies are favorable—and those where they are not a good fit. This report matches Brazilian market conditions to the expected characteristics and applications of SMRs and MRs, using criteria defined in the literature. Market conditions specific to each reactor size category and those shared between the two are examined. The importance of local conditions for MRs is discussed, but the lack of available data prevents conclusions on the fit of the Brazilian market at this time. Examining these factors allows decision makers in Brazil to determine whether the technology is a good fit for their specific use case and supports the overall decision-making process in the energy generation sector.

Sources to relevant datasets are provided when available to support future research as the technological and financial characteristics of SMR and MR designs become clearer. Without a better avenue for comparison, Brazil's characteristics are compared to those of similar countries to help provide additional context and the relative favorability of each criterion presented. The countries chosen for comparison are Argentina and Mexico. Like Brazil, both Argentina and Mexico are classified as upper-middle-income countries, according to (The World Bank 2022). Furthermore, like Brazil, both countries have an existing nuclear program and have expressed interest in SMR and MR technology.

2.3.1.1 Overview of the Brazilian Power System

Prior to the 1990s, the Brazilian Power System operated as a natural monopoly, with vertically integrated public utilities and no competition. In response to the financial troubles in the 1990s among the Brazilian Power System companies and in face of the need for new investments to meet the increasing domestic demand, Brazil began the process of restructuring its power system to establish a more competitive and efficient market to attract private investors. Today, Brazil has an unbundled electricity market in power generation, transmission, distribution, and commercialization. Even though there is competition in generation services, only large and medium-sized consumers have the right to choose their suppliers. This partial liberalization results in two market environments: the free market and the regulated market. In the regulated market, consumers are represented by their distribution companies, and the contracts for power generation occur via a "single buyer" mechanism in energy auctions. According to EPE (2022), the free market accounted for 38% of overall consumption in 2021 and 87% of industrial consumption.

In accordance with the Paris Climate Agreement, Brazil pledged to reach emission reductions of 37% by 2025 and 50% by 2030, compared to 2005 levels. Compared to the rest of the world, Brazil's energy matrix is already a standout in terms of renewable energy generation. Hydroelectric generation comprised 63% of total national electricity generation in Brazil in 2021. Besides hydroelectric, the remaining electricity generation in 2021 was supplied by fossil-fired plants (13%), VRE resources (12%), biomass (9%), and nuclear (2%). With a high reliance on hydroelectric, Brazil faces reliability challenges due to recent droughts and long distances between hydropower plants and most of the population. To diversify the energy mix and follow through with NDC commitments, Brazil plans to increase investment in non-hydroelectric renewables, especially wind and solar. According to EPE's 2031 Ten-year Energy Expansion Plan (EPE 2022), Brazil expects the combined installed capacity of wind and solar sources to reach 40 GW by 2031, only considering the centralized generation. Renewable distributed generation may reach 48 GW by 2031 alone.

Brazil also plans to add a third NPP to their large reactor fleet, which currently consists of the 609 MWe Angra 1 NPP and the 1,275 MWe Angra 2 NPP. The Angra 3 NPP, with an installed capacity of 1,340 MW, is expected to be completed by 2027. Eletronuclear is one of the owner-operators of NPPs in Brazil. With the increased penetration of VRE resources and a lower reliance on hydropower, Brazil may also face challenges supplying flexible, reliable, low-emissions, cost-effective power.

2.3.2 Market Assessment Methodology

This methodology leverages two reports that include methodologies that can be used to assess the potential market suitability for SMR and MR deployment. The methodologies are applied to Brazilian economic and market conditions for consideration of generic types of SMR and microreactor technologies. The first report is the IAEA Deployment Indicators for Small Modular Reactors: Methodology, Analysis of Key Factors, and Case Studies (IAEA 2018), called the IAEA Report henceforth. The second report is the Global Market Analysis of Microreactors (Shropshire et al. 2021), called the Global Market Report henceforth.

The IAEA Report's methodology for assessing SMR feasibility in member states contains two parts. Part One covers initial conditions or gate conditions, which are detailed in Section 2.3.2.1. While these gate conditions are only presented for SMR feasibility in the IAEA Report, they are also applicable for assessing MR feasibility. The second part of the IAEA Report covers 18 deployment indicators to help determine the suitability of adding SMRs to a nation's energy portfolio. These 18 deployment indicators from the IAEA Report are discussed in Section 2.3.2.2.

Like the gate conditions, some of the 18 indicators also apply to MR deployment. Therefore, utilizing the IAEA Report as a framework for their report, the authors of the Global Market Report modified and added indicators specifically applicable to MR deployment. Given the differences in size and characteristics between SMRs and MRs, the authors of the Global Market Report developed indicators that evaluate more local conditions, an important consideration for MR deployment. Section 2.3.2.2 presents the MR-specific indicators developed in the Global Market Report.

2.3.2.1 Must-Pass Gate Conditions and Optional Initial Conditions

The IAEA Report presents three gate conditions that are must-pass for a nation's market to be suitable for SMR deployment. We evaluated these necessary conditions to determine if SMR and MR deployment is practical in Brazil and if further evaluation should proceed.

The first condition examines the size of a nation's electric grid and is passed if (a) the nation's electric grid is greater than 1.5 GWe and (b) the size of the SMR makes up less than 10% of total grid capacity. Brazil's electric grid capacity in 2019 was 188 GWe (U.S. EIA 2022), well above the 1.5 GWe threshold. Furthermore, even a 300 MWe SMR would be less than 10% of Brazil total grid capacity. Thus, Brazil passes the first gate condition.

The second gate condition considers a nation's ability to invest in incipient technologies. Although MRs are expected to have lower capital costs compared to SMRs, sufficient financial and economic resources are necessary for practical deployment both of SMRs and MRs in Brazil. The IAEA's minimum threshold for this condition is U.S. $20.2 billion purchasing power parity (PPP), the lowest gross domestic product (GDP) among countries developing a nuclear program. Not only does Brazil already have a nuclear program but passes this gate condition with a GDP (PPP) of $3.153 trillion in 2020 (The World Bank 2022). PPP indicates the value of a currency compared to another. PPP "adjusts for disequilibria in exchange rates." This metric also captures GDP per capita, which is associated with higher energy demand.

According to the IAEA Report, a nation's market is deemed suitable for SMR and MR deployment if a sufficient level of per capita GDP is achieved. The IAEA determines the minimum per capita GDP as $2,588 USD (PPP) in 2011, roughly the same buying power as $3,040 USD (PPP) in 2020 (U.S. Bureau or Labor Statistics 2020). Brazil had a per capita GDP in 2020 of $14,835 USD (PPP), thus passing the third gate condition (The World Bank 2022).

2.3.2.2 Market Indicators for Assessing Small Modular Reactor and Microreactor (MR) Deployment Suitability

The following indicators help decision makers in Brazil and potential investors outside the country determine market suitability for SMRs and MRs. These indicators were developed based on the general understanding and expectation of SMR and MR technological characteristics. Section 2.3.2.2 presents the IAEA indicators for SMR and MR deployment.

Small Modular Reactor Indicators

Table 15 presents the six categories and 18 total indicators developed by the IAEA. Following the table, we present a brief description of each indicator, including what issues they address and where to source this information and data. For a more detailed description of these indicators and how they are calculated, reference the IAEA Report.

Table 15. SMR indicators by category.

National Energy Demand	SMR Energy Demand	Financial/ Economic Sufficiency	Physical Infrastructure Sufficiency	Climate Change Motivation	Energy Security Motivation
Growth of Economic Activity (GDP GWTH)	Dispersed Energy (RURAL)	Ability to Support New Investments (GDP/PC-GDP)	Electric Grid Capacity (GRID)	Reduce CO_2 Emissions per Capita (CO_2)	Reduce Energy Imports (ENG IMP)
Growth Rate of Primary Energy Consumption (GRPEC)	Cogeneration (DESAL/DH)	Openness to International Trade (FDI/TRADE)	Infrastructure Conditions (INFRA)	Reduce Fossil Fuel Energy Consumption (FOSSFUEL/OGC)	Use Domestic Uranium Resources (URAN)
Per Capita Energy Consumption (PC-EC)	Energy Intensive Industries (EII)	Fitness for Investment (CREDIT)	Land Availability (LAND)	Achieve NDC Carbon Reduction Goals (NDC)	Balance Intermittent Renewables (RES)

The first category is National Energy Demand. National energy demand data is important to evaluate if a country has a need for energy provided by a reactor both currently and in the future.

- Growth of Economic Activity (GDP GWTH)
  - It is favorable for SMR deployment for countries to have positive economic growth, as this factor is typically associated with greater energy demand. Additionally, larger growing economies are more able to meet the capital investment requirements of large projects.
  - Source: World Bank
- Growth Rate of Primary Energy Consumption (GRPEC)
  - Countries with an increasing need for energy production are favorable for SMR deployment because they must add capacity to meet needs. Although these countries may not utilize nuclear

  power, they need some type of generation technology and thus are more likely to adopt nuclear than countries with negative demand growth.
  - Source: Total Primary Energy Consumption, U.S. EIA
- Per Capita Energy Consumption (PC-EC)
  - A high per capita energy consumption signifies that a country will likely experience demand growth and be induced to utilize additional generation in the future. This raises the likelihood of SMR adoption.
  - Source: World Bank

The second category covers SMR Energy Demand indicators. This category aims to help member states evaluate the suitability of their infrastructure, market, and geography for SMR deployment.

- Dispersed Energy (RURAL)
  - This measure indicates market dispersion, which is typically associated with population concentration. More rural countries can have a greater need for technologies like SMRs for multiple reasons, including the costs and losses associated with electricity transmission and the desire for distributed and resilient generation. Large municipalities typically utilize very large generation assets, a behavior not shared by more rural areas.
  - Source: World Bank
- Cogeneration (DESAL/DH)
  - Some SMR concepts can produce both heat and electricity. This opens a set of opportunities not available to other energy generation technologies. Thermal applications for SMRs include desalination (salt removal from saltwater and brackish water, which can utilize either or both thermal or electric energy) and district heating (providing heat for multiple buildings). Countries with demand for these technologies are more likely to utilize SMR technology.
  - Source: Global Water Intelligence, University of Melbourne Victoria
- Energy Intensive Industries (EII)
  - EII, especially those far from concentrated populations, tend to be difficult to decarbonize. Some of these industries utilize both electric and heat energy—both of which many SMR concepts can produce. As such, a higher demand of energy for EIIs is favorable for SMR adoption.
  - Source: IEA

The third category of indicators is Financial/Economic Sufficiency. This group of indicators aims to evaluate a country's economic and financial conditions and shed light on the demand conditions of their energy markets.

- Ability to Support New Investments (GDP/PC-GDP)
  - As capital-intensive projects, SMRs require that a country can support new investments. A high GDP also indicates that a country likely has a larger need for energy. Both factors lead to favorable conditions for SMR adoption when met.
  - Source: World Bank
- Openness to International Trade (FDI/TRADE)
  - This metric captures a proxy for the amount of trade flows in a country. This shows the willingness of the country to accept foreign investment and foreign entities' willingness to invest in projects in the country. A higher openness to international trade is favorable for SMR adoption.
  - Source: World Bank

- Fitness for Investment (CREDIT)
  - Financing for capital-intensive projects is a necessary factor. To obtain financing, countries must have a relatively high credit rating, which means that the country has a lower likelihood to default on loans. Countries with a lower credit rating may be less likely to obtain financing or may be required to pay higher interest rates for new energy projects like SMRs. This can contribute significantly to overall project costs.
  - Source: World Bank or Standard & Poor's Credit Rating

The fourth category contains three indicators used to evaluate a country's physical infrastructure sufficiency. These indicators aim to evaluate a country's nonfinancial feasibility for SMR deployment.

- Electric Grid Capacity (GRID)
  - Electricity grids must be large enough to reasonably utilize large baseload energy generation assets. The benchmark for this indicator is that the SMR capacity should not be larger than 10% of the total grid.
  - Source: EIA's International Energy Statistics 2019
- Infrastructure Conditions (INFRA)
  - This metric examines a county's physical infrastructure, from "transportation [and] communications, [to] electrical distribution networks." Countries with a more developed infrastructure are more likely to both need and be able to support SMRs.
  - Source: World Economic Forum (WEF's) annual Global Competitiveness Report.
- Land Availability (LAND)
  - SMRs require less land for siting than large NPPs—as such, countries with denser populations may be more suited for SMR use.
  - Source: *World Urbanization Prospects,* Population Division of the UN's Department of Economic and Social Affairs.

The fifth category covers Climate Change Motivation indicators. These indicators aim to address the country-specific incentives present that may motivate the adoption of carbon-free generating resources.

- Reduce CO_2 Emissions per Capita (CO_2)
  - With increasing impacts of climate change, countries with higher CO_2 emissions are more likely to adopt measures to reduce emissions. This is because, as time passes, the internal and external incentives and disincentives leveraged on high-emission countries will likely increase. As such, these countries are more likely to adopt SMRs because the technology stands out as one of the few consistent and carbon-neutral energy generation methods.
  - Source: World Bank

- Reduce Fossil Fuel Energy Consumption (FOSSILFUEL/OGC)
  - High reliance on fossil fuels results in higher CO_2 emissions. As international pressures to decarbonize increase, fossil fuels will likely become more expensive over time as regulations create policies, like carbon taxes or restricting supply. As the world shifts away from carbon-emitting resources due to climate change, countries with a higher reliance on fossil-fueled assets may have a greater impetus for SMR adoption.
    Source: World Bank
  - Like the measures above, the OGC indicator examines a country's motivation to decarbonization. However, this indicator specifically measures the oil, gas, and coal capacity as a percentage of total capacity. With pressures to decarbonize, countries with a high reliance on high-carbon fuels are more likely to adopt low-carbon emission sources like SMR technology.
  - Source: UNFCCC NDC Registry

The sixth and final category of indicators evaluates energy security, especially using low-carbon and domestic energy sources.

- Reduce Energy Imports (ENG IMP)
  - Countries that are reliant on out-of-country energy generation are more likely to expand domestic production to be more self-reliant. Given planned capacity expansion, these countries are more likely to utilize SMR technology.
  - Source: World Bank
- Use Domestic Uranium Resources (URAN)
  - If countries have domestic uranium resources, they may be more likely to adopt SMRs as they could potentially lower fuel costs by avoiding uranium imports. Additionally, domestic materials reduce the risks associated with international supply chains, regulations concerning uranium transport, and international politics.
  - Source: "Uranium 2014: Resources, Production, and Demand Report," also known as the Red Book, jointly produced by the OECD's Nuclear Energy Agency (NEA) and the IAEA
- Balance Intermittent Renewables (RES)
  - The larger the penetration of VREs within an electrical grid, the more storage or dispatchable generation is required to always meet needs. Some SMR concepts are designed to be flexible, allowing them to adjust output to balance productions with current needs. Countries with a larger generation share of VREs are more likely to adopt SMRs with ramping capabilities.
  - Source: NDC targets or other national-level plans

Microreactor (MR) Indicators

Authors of the Global Market Report reviewed the IAEA Report to determine which SMR deployment indicators are also applicable to MR deployment. The authors of the Global Market Report concluded that some of the SMR indicators, highlighted in yellow in Table 16, are only applicable to MR deployment as minimum conditions at a national level for practical MR deployment. In other words, these benchmarking indicators evaluate if MRs should be considered in a country's overall energy development strategy.

Given the size and different capabilities of SMR and MRs, the authors of the Global Market Report argue that localized indicators are more relevant in determining MR deployment suitability. As such, the authors of the Global Market Report developed 12 MR-specific indicators that help evaluate if local conditions are amenable to MR deployment. While the IAEA Report utilized national-level data for assessing deployment conditions for SMRs, the MR-specific indicators developed in the Global Market

Report require local data sources. National-level data is generally more available—but the ability to evaluate the suitability of MR deployment in locations within a country depends on local data.

Table 16 below presents the MR deployment indicator table from the Global Market Report. As previously mentioned, yellow cells indicate benchmarking indicators leveraged from the IAEA Report. Green cells represent MR-specific indicator additions, and grey cells represent IAEA SMR deployment indicators that are not applicable to MR deployment. Since the nine benchmarking indicators were already covered in Section 2.3.2.2, this section focuses on describing the MR-specific indicators. For more information on how the MR-specific indicators were developed, reference the Global Market Report.

Table 16. Microreactor deployment indicator categories.

National Energy Demand	Microreactor Energy Demand	Financial/ Economic Sufficiency	Physical Infrastructure Sufficiency	Climate Change Motivation	Energy Supply Surety Motivation
Growth of economic activity (GDP GWTH)	Dispersed energy/remote/ land/locked (DISP/R/L)	Ability to support new investments (GDP/PC-GDP)	Electric grid capacity (GRID)	Reduce CO_2 emissions per capita (CO_2)	Reduce energy imports/diversify energy sources (ENG IMP/DIV)
Growth rate of primary energy consumption (GRPEC)	Local cogeneration (LOC COGEN)	Openness to international trade (FDI/TRADE)	Limited access to energy (LAE)	Reduce fossil fuel energy consumption (FOSSFUEL/OGC)	Use domestic uranium resources (URAN)
Per capita energy consumption (PC-EC)	Local energy intensive industries (LEII)	Fitness for investment (CREDIT)	Land availability (LAND)	Achieve carbon reduction goals (NDC)	Balance intermittent renewables/ scalability (RES/SCALE)
Local economic growth potential (LEGP)	Local energy price premiums/ seasonal (LEPP/S)	Limited access to local capital (LOCCAP)	Limited access to trades/QA (TRADES/QA)	Local climate change/disaster vulnerability (LCC/DV)	Local critical loads/facilities (CRIT)

Microreactor-specific indicator	Microreactor-benchmarking indicator	Not applicable to microreactors

The first category is National Energy Demand. This indicator specifically considers the economic growth and likely commensurate growth in the energy demand of a localized economic region.

- Local Economic Growth Potential (LEGP)
  - Because the growth of the economy and energy demand are correlated, this metric is used as a proxy for energy demand changes. Positive economic growth is favorable for MR adoption.

The second category presents indicators for MR-specific energy demand. These indicators help evaluate the number of MRs that could potentially be utilized to meet needs.

- Dispersed Energy/Remote/Land-locked (DISP/R/L)
  - Microreactors are a good fit for dispersed energy consumers given the costs and losses associated with transmission and some users' need for highly reliable generation. Off-grid and isolated

  - energy users, land-locked locations, and island locations are conducive consumers for microreactors, given the MR size, transportability, and independent operation capability. As such, a higher value for this metric is favorable for MRs.

- Local Cogeneration (LOC COGEN)
  - Demand for heat and electricity cogeneration is positively correlated with the likelihood of adoption of MRs with matching characteristics.
- Local Energy Intensive Industries (LEII)
  - As explained in the SMR section, LEIIs are often difficult to decarbonize. These industries may also have a higher need for reliability, both of which match well with MR technical characteristics.
- Local Energy Price Premiums/Seasonal (LEPP/S)
  - Based on unique characteristics, some locations may experience higher energy prices. These locations are more likely to adopt MRs because the threshold for cost competitiveness is lower.

The third category of indicators is Financial/Economic Sufficiency. This group of indicators helps determine a locality's ability to finance capital-intensive projects.

- Limited Access to Local Capital (LOCCAP)
  - Local financial conditions may promote or prohibit accumulation of capital for the initial costs associated with microreactor adoption. MRs have smaller capital costs as compared to SMRs and thus require less financing.

The fourth category contains five indicators used to evaluate a country's physical infrastructure sufficiency.

- Limited Access to Energy (LAE)
  - If a local area has limited existing access to energy (for example, less transmission or generation capacity), it may be more likely to adopt SMRs to meet its own energy needs.
- Limited Access to Trades/QA (TRADES/QA)
  - If a location has limited access to trades, it may be more likely to utilize SMR technology given the relative simplicity and lower construction requirements of SMR utilization.

The fifth category covers Climate Change Motivation indicators.

- Local Climate Change/Disaster Vulnerability (LCC/DV)
  - If a location is likely to experience natural disasters, it may be more likely to purchase a MR given that the asset could be deployed to a different location during an emergency.

The sixth and final category of indicators examines the electrical grid and energy users within an area, from both generation and consumption perspectives. This capture needs outside traditional load-matching considerations.

- Reduce Energy Imports/Diversify Energy Sources (ENG IMP/DIV)
  - Like the SMR indicator, locations may desire to reduce the amount of energy they import to be more self-sufficient or to diversify energy generation technologies to have more reliable coverage. These factors make localities more likely to adopt MRs.
- Balance Intermittent Renewables/Scalability (RES/SCALE)
  - Also mentioned in the SMR section, a higher penetration of VREs leads to an increased need to balance load under increased generation variability. Load following MRs could help meet this

  - need reliably. Additionally, as required generation changes over time, single MR units can be added or removed to meet needs with relatively small capital investment.
- Local Critical Loads/Facilities (CRIT)
  - Some energy users have an extreme need for reliability (i.e., data centers, hospitals, military centers). Also, disaster response requires electricity generation in the area. MRs can meet both needs with transportability and high reliability.

Section 2.3.2 introduces and describes indicators used to determine the relative favorability of SMRs and MRs for applications in Brazil. The meaning and importance of these indicators is also discussed. These factors will be utilized in subsequent sections to conduct the favorability analysis.

2.3.3 Brazilian Market Indicators

Section 2.3.3 applies the 18 IAEA developed market indicators for Brazil. We first present an overview of the results. This overview is followed by a detailed dive into the value of each indicator for Brazil, what this means for the relative suitability of the Brazilian market in terms of each indicator, and where to source these data. Given that the IAEA Report doesn't go into detail on how to rank according to their decile system, and similar to the Puerto Rico Report (The Nuclear Alternative Project 2020), we compared Brazilian data points to other upper-middle-income countries that already maintain a nuclear program, Mexico and Argentina.

Each indicator is marked as Favorable, Neutral, or Unfavorable relative to data from Mexico and Argentina and to the average upper-middle-income country. Indicators that are marked Favorable imply that the Brazilian market is relatively positive for SMR deployment and vice versa for indicators marked Unfavorable. A detailed description of why each indicator is marked Unclear is provided. Note that these designations are relative and do not comment on the absolute favorability of Brazil for SMR adoption.

Table 17 presents an overview of the suitability of the Brazilian market by indicator from a national-level perspective. As can be seen from the table, the Brazilian market data is Favorable, Neutral, and Unfavorable for SMR deployment depending on the indicator. Three indicators are marked Unfavorable, two indicators are marked Neutral, and the remaining 13 indicators are marked Favorable relative to the comparison countries. Each indicator is described in more detail in Subsections 2.3.3.1–2.3.3.6.

Table 17. National indicator results summary.

🟩 Relatively Favorable ⬜ Neutral 🟥 Relatively Unfavorable

National Energy Demand	SMR Energy Demand	Financial/ Economic Sufficiency	Physical Infrastructure Sufficiency	Climate Change Motivation	Energy Security Motivation
🟩 Growth of Economic Activity (GDP GWTH)	🟥 Dispersed Energy (RURAL)	🟩 Ability to Support New Investments (GDP/PC-GDP)	🟩 Electric Grid Capacity (GRID)	⬜ Reduce CO_2 Emissions per Capita (CO_2)	🟥 Reduce Energy Imports (ENG IMP)
🟩 Growth Rate of Primary Energy Consumption (GRPEC)	🟩 Cogeneration (DESAL)	🟩 Openness to International Trade (FDI/TRADE)	🟩 Infrastructure Conditions (INFRA)	⬜ Reduce Fossil Fuel Energy Consumption (FOSSFUEL/OGC)	🟩 Use Domestic Uranium Resources (URAN)
🟩 Per Capita Energy Consumption (PC-EC)	🟩 Energy Intensive Industries (EII)	🟥 Fitness for Investment (CREDIT)	🟩 Land Availability (LAND)	🟩 Achieve NDC Carbon Reduction Goals (NDC)	🟩 Balance Intermittent Renewables (RES)

2.3.3.1 *National Energy Demand Indicators*

These first three indicators are applicable to both SMR and MR deployment and are presented from a general, nationwide market perspective. As presented above in Section 2.3.2.2, these indicators attempt to evaluate a nation's demand conditions for energy. All three indicators are linked in the sense that if GDP is growing, commensurate increases in GRPEC and PC-EC are also expected. These indicators help a nation assess if their overall economic activity is sufficient for SMR and MR investment.

Table 18. Energy demand indicators.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
GDP GWTH	GDP growth (annual %, 2015-2019 average)[1]	-0.46%	2.01%	-0.23%	(The World Bank 2022)
GRPEC	Primary consumption 2009-2019 (Quadrillion Btu, year-to-year growth averaged)	1.94%	0.57%	0.33%	(U.S. EIA 2022)
PC-EC	Energy use (kg of oil equivalent per capita)	1,495	1,537	2,030	(The World Bank 2022)

[1] Note that while 2020 data on GDP GWTH are available from the World Bank, that data is omitted here due to the worldwide negative economic impacts of the COVID-19 pandemic.

According to the World Bank, Brazil's GDP shrunk an average of 0.46% per year between 2015 and 2019. For comparison, Mexico's economy grew 2.01% during the same period and Argentina's economy shrank, albeit less than Brazil's. Although an average annual negative GDP change for Brazil doesn't suggest strong economic growth, the trend presented in Figure 8 below provides further insight. Despite negative GDP growth in 2015 and 2016, Figure 8 shows that Brazil's economy grew between 1–2% per year from 2017 to 2019. Note that while 2020 data on GDP GWTH are available from the World Bank, that data is omitted here due to the worldwide negative economic impacts of the COVID-19 pandemic.

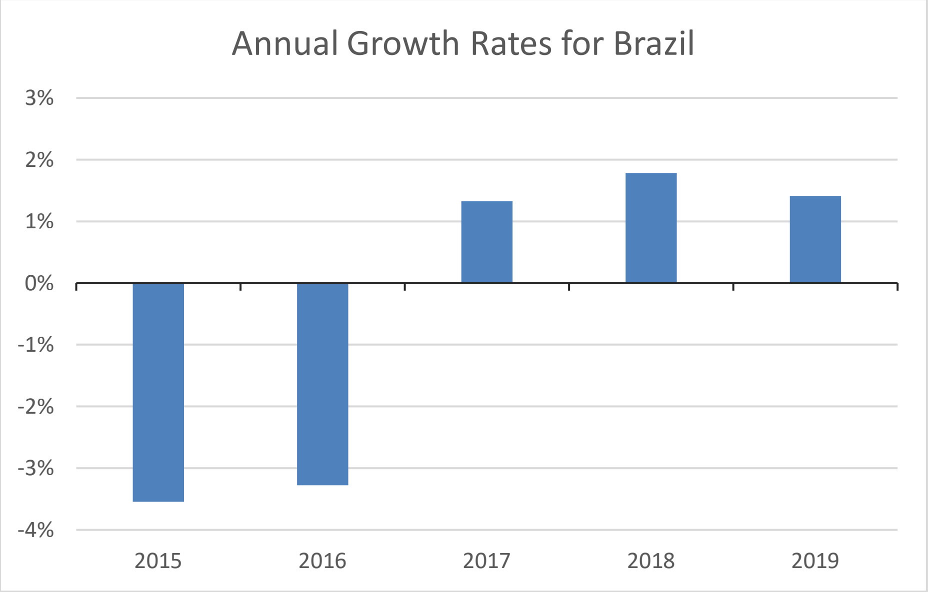


Figure 8. Annual growth rates for Brazil. (The World Bank 2022)

The Brazilian datapoint for the GRPEC indicator is 1.94%, roughly three times larger than Mexico's and almost six times larger than Argentina's. According to the latest values available from the World Bank, the PC-EC for Brazil is 1,495 kg of oil equivalent use per capita, smaller than the values for Mexico and Argentina. Even though the Brazil PC-EC is the lowest, Brazil's kg of oil equivalent use per capita trend is positive from 2004 to 2014 (2.79% growth). Considering the positive trends in GDP GWTH and PC-EC for Brazil and the high GRPEC compared to Mexico and Argentina, these three indicators are marked as Favorable for Brazil.

2.3.3.2 Small-Modular-Reactor-Specific Demand Indicators

The indicators in this category only apply to SMR deployment and therefore are presented from a general, nationwide market perspective. These indicators help Brazil assess its suitability for SMR adoption. The first indicator in Table 19 is RURAL, the percent of the total population located in rural areas. Compared to Mexico and Argentina, Brazil falls in the middle, with 12.93% of its population living in rural areas. On average, about 32% of all upper-middle-income countries' population is rural. Compared to the average of all upper-middle-income countries, Brazil falls below. Given Brazil's RURAL indicator datapoint relative to the average of all upper-middle-income countries, this indicator is marked Unfavorable.

Table 19. SMR demand indicators.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
RURAL	Rural population (percent of total population)	12.93%	19.27%	7.89%	(The World Bank 2022)
DESAL/DH	Annual increment to contracted capacity forecast (2007–2016 average)	Brazil, Mexico, and Argentina all currently possess desalination capacity and are expected to increase capacity in the future due to ongoing water availability challenges			(BCC Research 2016)
	Köppen-Geiger climate classification	81.4% Tropical climate (A zone), 4.9% Semi-arid climate (B zone), and 13.7% Subtropical climate (C zone)	Northern Mexico is mostly a Semi-arid climate (B zone), and southern Mexico is mostly a Tropical climate (A zone)	The Northwest coast and the South are a Semi-arid climate (B zone), and the northeast is mostly a temperate climate (C zone)	Brazil: (Alvares, Stape et al. 2013) México and Argentina: (Kottek, Grieser et al. 2006)
EII	Energy use in iron and steel, nonferrous metals, mining, and pulp and paper (thousands of tons of oil equivalent, ktoe)	37,083 ktoe, industry comprises 30.3% of total final energy consumption	In 2014, industry comprised 28% of final energy consumption and is expected to comprise 31% in 2040	Unknown	Brazil: (EPE 2020) Mexico: (IEA 2016)

The next two indicators assess Brazil's suitability for nonelectric SMR applications, like desalination and district heating. According to a report on the global market for seawater and brackish water desalination by BCC Publishing, (BCC Research 2016), significant growth in desalination capacity for drinking water is forecasted for Brazil. In the water-stressed state of Ceará, the state water utility plans to increase water supply capacity by 12% with the construction of the country's largest desalination plant (Andrade 2019). While Brazil has large water resources, those resources are not easily accessible by the majority of the population. Since most of the water reserves are located in the Amazon and most of the population is located on the east coast, 30% of available water resources must supply 95% of the population (Silva et al. 2018). Given Brazil's challenges with the supply and demand of water, the construction of a new desalination plant, and the significant capacity growth forecasted, this indicator is market Favorable.

The DH indicator is evaluated using the Köppen-Geiger climate classification system. Given the country's proximity to the equator, the climate in Brazil is mostly classified as tropical and enjoys an annual mean temperature of 20°C or greater (Alvares et al. 2013). With such warm temperatures, DH is not an SMR cogeneration application suitable in Brazil. This indicator is therefore not applicable and is not discussed any further.

The fourth indicator in this category, EII, aims to evaluate if amenable market conditions exist in Brazil for process-heat SMR applications. In 2019, industry made up 30.3% of total final energy consumption in Brazil. According to the IAEA definition of EII, 14.2% of that 30.3% was consumed by EII as shown in Figure 9 (EPE 2020). The industrial sector is an important to the Brazilian economy, roughly accounting for 16% of Brazil's 2019 GDP. Comparatively, the industrial sector in Mexico is expected to comprise 31% of total final energy consumption by 2040. Given the industrial sectors importance in the Brazilian economy and its high energy demands, the EII indicator is marked Favorable.

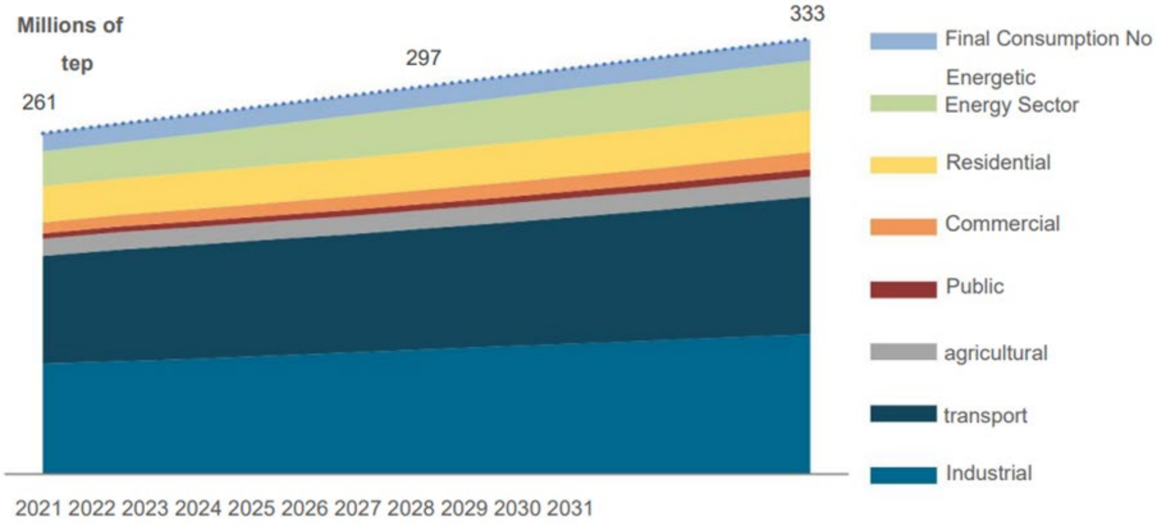


Figure 9. Final energy consumption by sector. Data sourced from (EPE 2022).

2.3.3.3 Financial and Economic Sufficiency Indicators

This category of indicators assesses the financial and economic conditions of the Brazilian economy. The first indictor is GDP. Brazil had a GDP of $3.153 trillion in 2020. Compared to the GDPs of Mexico and Argentina in 2020, Brazil's GDP is the highest. In terms of GDP per capita, however, Brazil is roughly $3,600 less than Mexico and $6,000 less than Argentina. These two indicators aim to evaluate Brazil's ability to support new investments. Larger economies, represented by a high GDP and high PC-GDP, indicate an ability to finance SMR purchases and the potential demand for multiple units. Given the relative magnitude of Brazil's GDP and PC-GDP compared to Mexico and Argentina, these indicators are marked as Favorable. Note that while the three countries were impacted by the COVID-19 pandemic in 2020, the World Bank data show the relative trend of GDP across the three countries remained similar to pre-pandemic years.

Table 20. Financial and economic sufficiency.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
GDP/ PC-GDP	GDP, PPP (current international $)	$3.153 trillion	$2.378 trillion	$942.508 billion	(The World Bank 2022)
	GDP per capita, PPP (current international $)	$14,835.42	$18,444.10	$20,770.73	(The World Bank 2022)
FDI/ TRADE	Foreign direct investments, net inflows (BoP, current USD)	$37.786 billion	$31.049 billion	$6.663 billion	(The World Bank 2022)
	Trade (percent of GDP)	32.35%	78.20%	30.15%	(The World Bank 2022)
CREDIT	External debt stocks, total (DOD, current USD)	$549.234 billion	$467.511 billion	$253.76 billion	(The World Bank 2022)
	Standards & Poor (S&P) ratings index	BB-/B	BBB	CCC+/CCC	(S&P Global Ratings 2020)

The FDI and TRADE indicators help evaluate the Brazilian economy in terms of openness to international trade. The FDI indicator aims to capture the amount of trade flow in the Brazilian economy. Compared to Mexico and Argentina, Brazil's net inflow of FDI is larger. The TRADE indicator aims to capture the overall level of international trade. As a percent of total GDP in Brazil, trade made up 32.35% in 2020 and has been growing over the last decade, 3.88% per year on average. Trade as a percent of GDP was slightly greater than Argentina and much less than Mexico in 2020. The 2020 TRADE indicator for the upper-middle-income group was 44.11%. Given the positive trend of Brazil's TRADE indicator and Brazil's comparatively high FDI value, the FDI and TRADE indicators are marked Favorable.

The CREDIT indicator aims to capture Brazil's fitness for investment in a new energy project. According to the IAEA, low external debt or a high credit rating are favorable conditions for obtaining financing and low interest rates. Compared to Mexico and Argentina, Brazil holds the highest amount of external debt. An alternative method to determine credit worthiness is to look at Standards & Poor's (S&P) credit rating. Of the three countries, Mexico's government bonds are the only ones rated as investment grade. S&P rated Brazilian government bonds as BB-/B, which is considered below investment grade. Given the higher amount of external debt held by Brazil compared to Mexico and Argentina and the below investment grade credit rating, we mark the CREDIT indicator as Unfavorable.

2.3.3.4 Physical Infrastructure Sufficiency Indicator

The GRID indicator is the same as the first gate condition. Brazil had a total installed electricity capacity of 188 GWe in 2019, compared to 84 GWe in Mexico and 43 GWe in Argentina. With a grid size greater than 1.5 GWe, the size of electricity market demand and suitability of SMRs in Brazil seems reasonable. Thus, the GRID indicator is marked Favorable.

Table 21. Physical infrastructure sufficiency.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
GRID	Total electricity installed capacity (GWe)	188	84	43	(U.S. EIA 2022)
INFRA	Infrastructure (rank)	78/141	54/141	68/141	(World Economic Forum 2019)
LAND	Urbanization rate	87%	80%	92%	(United Nations Department of Economic and Social Affairs 2018)

The INFRA indicator aims to capture the condition of Brazil's national physical infrastructure, including transportation, communications, and electrical distribution network. Brazil's infrastructure ranked 78th out of 141 countries, higher than both Mexico and Argentina. Comparatively, Brazil's higher infrastructure makes Brazil a more amenable country for SMR adoption. Therefore, we mark the INFRA indicator as Favorable.

The LAND indicator evaluates the availability of land within a country with access to utility systems to potentially site SMRs. Higher urbanization rates represent countries without much space for distributed energy systems. With limited space, these countries require more compact power systems, a condition amenable to SMR deployment. The urbanization rate of all three countries is high, with more than 80% of their populations living in urban areas. Brazil's LAND indicator falls in the middle compared to Mexico's LAND indicator of 80% and Argentina's LAND indicator of 92%. Given the relatively high LAND indicator for Brazil, we mark this indicator as Favorable.

2.3.3.5 Climate Change Motivation Indicators

The per capita CO_2 emission in 2018 of the average of the upper-middle-income countries was 6.24 metric tons. Compared to the average of the upper-middle-income countries, which includes Brazil, Mexico and Argentina, Brazil has a relatively low CO_2 emission per capita. Furthermore, Brazil's CO_2 indicator is lower than both Mexico and Argentina. Almost 66% of Brazil's electricity is generated from hydroelectric resources (U.S. EIA 2021). Since hydroelectric is a renewable, non-Greenhouse Gas (GHG) emitting resource, Brazil's lower CO_2 indicator is unsurprising. With the challenge of climate change looming, the IAEA Report argues that countries with higher levels of CO_2 emission are more amenable for SMR adoption.

Table 22. Climate change motivation.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
CO2	CO_2 emissions (metric tons per capita)	2.042	3.741	3.987	(The World Bank 2022)
FOSSFUEL/OGC	Fossil fuel energy consumption (percent of total)	59.11%	90.43%	87.72%	(The World Bank 2022)
	Electricity production from oil, gas, and coal sources (percent of total)	23.43%	80.88%	66.94%	(The World Bank 2022)
NDC	Nationally determined contributions	37 and 50% reduction in GHG emissions by 2025 and 2030, respectively, compared to 2005 levels	22% reduction in GHG emissions and 51% reduction in black carbon by 2030	An 18% reduction in million tons of carbon dioxide equivalent (MTCO2e) by 2030, compared to 2005 levels	(United Nations Climate Change 2022)

The IAEA positively correlates the reliance on GHG emitting sources and SMR deployment. In 2014, the World Bank estimates that 59.11% of total energy consumption and 23.43% of total electricity production was on fossil fuels and from oil, gas, and coal sources, respectively. Compared to Mexico and Argentina, both the share of FOSSFUEL and OGC are relatively low.

The IAEA criteria would mark the Brazil indicators for FOSSFUEL, OCG, and CO2 as Unfavorable relative to Mexico and Argentina, given a lack of motivation to shift away from fossil-fired resources. While it may not be a motivating factor, Brazil's relatively low shares for the FOSSFUEL and OGC indicators and low CO2 indicator may not suggest an Unfavorable market for SMR adoption. We therefore mark these indicators as Neutral.

The NDC indicator aims to evaluate a country's motivation for replacing GHG emitting resources and lowering carbon emissions to address climate change. The more ambitious the NDC target, the more likely SMR adoption is. Compared to Mexico and Argentina's NDC targets, Brazil's target is more aggressive in reducing GHG emissions by 2030. As Brazil's target is relatively more aggressive, the NDC indicators is marked as Favorable.

2.3.3.6 Energy Security Motivation Indicators

The IAEA states that countries with higher net energy imports are more likely to be interested in becoming more self-reliant by developing more domestic production. Energy imports accounted for 11.87% of energy use in Brazil in 2015. The value for the ENG IMP indicator for the average of upper-middle-income countries and for Germany in 2015 was 28.01 and 61.4%, respectively. Given Brazil's relatively low percent of energy imports, the ENG IMP indicator is marked as Unfavorable.

Table 23. Energy security motivation.

Acronym	Dataset	Brazil	Mexico	Argentina	Data Source
ENG IMP	Energy Imports, net (percent of energy use)	11.87%	-4.67%	13.03%	(The World Bank 2022)
URAN	Uranium identified resources (sum of reasonably assured and inferred resources), <$130/kgU USD	267,100 tonnes U	2,900 tonnes U	18,500 tonnes U	(OECD Nuclear Energy Agency and IAEA 2014)
RES	Increasing share of renewable energy (wind and solar only)	Target of roughly 20% renewable share of total electricity generation by 2031	Target of roughly 31% renewable share of total final energy consumption by 2030	20% of power demand to be covered by renewable energy[1] generation with 10,000 MW added to the grid by 2025.	Brazil: (EPE 2022) Mexico: (IRENA 2015) Argentina: (Norton Rose Fulbright 2016)

[1] This includes hydropower, geothermal, biofuels, and tide as well as wind and solar.

The IAEA argues that countries with economically extractable uranium resources are more likely to be interested in nuclear development, such as SMR adoption. Compared to Mexico and Argentina, Brazil has a much larger economically extractable uranium resource. Given that Brazil already maintains a nuclear program, has expressed interest in SMR adoption, and the relative level of its uranium resources, we mark the URAN indicator as Favorable.

Some SMRs are expected to be able to provide load following capabilities, which can be important for the reliability of portfolios with a high penetration of VRE resources. An increasing share of VRE resources and a decreasing share of fossil-fired resources makes it increasingly difficult to consistently meet demand. As such, the IAEA argues that markets expected to increase the share of renewable energy represent markets that may be more interested in SMR deployment for times of low VRE production and cogeneration. By 2031, Brazil aims to reach a VRE resource share (of total electricity generation) of approximately 20% (EPE 2022). Relative the other countries, it is unclear if this is an ambitious reference, given that directly comparable data is not readily available. Given that nonhydroelectric renewables are the fastest growing additions to the generation mix (U.S. EIA 2021) and Brazil's plan to increase the share of VRE participation on the grid, we mark the RES indicator Favorable.

Section 2.3.3 and its subsections present the Brazilian values for the 18 IAEA SMR deployment indicators. First Section 2.3.3 starts by outlining the results using IAEA indicators to categorize each of the indicators as either Favorable, Neutral, or Unfavorable suitability for the Brazilian market compared to Argentina and Mexico. Subsections 2.3.3.1–2.3.3.6 then report on the specific Brazilian values with sources for each indicator and provides a discussion about the relative favorability of the Brazilian market indicators compared to the market indicators for Argentina and Mexico. Based on the data presented in this section, we mark three indicators as Relatively Unfavorable, two indicators as Neutral, and the rest as Relatively Favorable. Table 17 presents the categorization of the indicators by color and indicates that the Brazilian market is relatively favorable for most of the indicators analyzed. While this section provides general, marketwide conclusions about the suitability of the Brazil for SMRs compared to Argentina and Mexico, it is unable to provide any conclusions on the suitability of the Brazilian market compared to the rest of the world. This section does not attempt to provide conclusions on the likelihood of SMR adoption in specific locations, markets, or by reactor design. The following section, Section 2.3.4, analyzes the Brazilian market indicator suitability against the technical specifications of the EPE-chosen SMR designs to discuss relative design favorability.

2.3.4 International Atomic Energy Agency Indicators Across Selected Concepts

Section 2.3.4 presents information regarding the suitability of the four selected reactors concepts based on Brazilian market indicators and design specifications. Each of the three SMR designs chosen by EPE are analyzed against market indicators to determine which designs are relatively favorable or relatively unfavorable. Note that, while designs were previously discussed more generically, this section discusses specific design parameters and values. The technical assessment in this section requires more specific information to be listed in order to exhibit the process of design comparison for deployment suitability.

The IAEA indicators used to evaluate the Brazilian market are not site- or design-specific for SMR suitability. As such, design specifications do not impact the suitability of the Brazilian market for general national indicators like GDP GWTH. Put another way, if the Brazilian market indicator GDP GWTH is marked Relatively Favorable for SMR adoption, then given the non-site and non-design-specific viewpoint, none of the three SMR design concepts would be better or worse than the others. Only more specific site and design data would provide such insights.

The indicators presented in Table 24 are the only indicators where the suitability of the Brazilian market conditions may vary depending on concept-by-concept technical specifications. The seven indicators include:

- RES: Designs with the ability to load follow to integrate with VREs would be more suitable.
- DESAL: Designs with the ability to provide combined heat and power to support desalination would be more suitable.
- EII: Designs with the ability to provide combined heat and power to support industrial process heat for energy intensive industries would be more suitable.
- LAND: Given the high percentage of Brazilians living in urban areas, designs with small footprints and EPZs may be more suitable for siting closer to urban centers.
- GDP: Designs that are cost competitive with other generation resources would be more suitable, and furthermore, a lower cost means lower financial risk to the investors.
- CREDIT: Fitness for investment may determine interest rate and financial risk.
- URAN: Using domestic uranium resources would be more valuable.

Table 24. Indicators by concept.

Design					
Indicator	Technical requirements	Water-based SMR between 200 and 300 MWth (NuScale)	Molten salt-fueled SMR between 500 and 600 MWth (ThorCon)	High-temperature gas-cooled SMR between 200 and 300 MWth (XE-100)	Heat-pipe-based microreactor with power less than 20 MWth (eVinci)
RES	Modularity/scalable power generation	Standard is four, six, or 12 (924 MWe) modules, possibly more	2 × 250 MWe modules is standard, up to 1 GWe per plant (four modules)	80 MWe modules can be scaled into a “four-pack” of 320 MWe, scale can grow as needed	Independent but connected units allow scalability to meet power demand growth
	Load following (x–100%, percent per minute)	Up 3%/min, down 10%/min	40–100% electrical power, 5–10%/minute	100–25–100% at a 5%/min ramp rate	High-speed load following capability
DESAL	Coproduce electricity and heat, reactor coolant outlet temperature	321°C, 250 MWth available per module for process heat	704°C	750°C, high-quality steam at 565°C	600°C, 7–12 MWth available for process heat
EII	High TRLs/maturity of designs	DCR application under review (U.S.)	Under review (Indonesia)	Pre-application activities (U.S.)	Pre-application activities (U.S.)
	High-capacity factors for reliability	>95%, can operate in island mode with black-start capability	90%, Plant can remain on warm standby island mode in the case of loss of load	95%, can operate at 75% of rated power in island mode indefinitely, black-start capability with onsite diesel gen sets	98%, can operate in island mode with black-start capability
LAND	Ease of siting (small EPZs)	Site boundary	0.5 km, or plant boundary, specifically a shoreside plant	0.4 km	Near-zero EPZ and small site footprint (<0.5 acres)
GDP	Overnight capital costs (OCC), loan size	According to (Mignacca and Locatelli 2020), OCC for SMRs are expected to cost between $2,000 and $8,000/kWe See Figure 10, which shows a general range for overnight capital cost by kWe for multiple SMR concepts and configurations			According to the (Nichol and Desai 2019), OCC for MRs are expected to range between

Design					
Indicator	Technical requirements	Water-based SMR between 200 and 300 MWth (NuScale)	Molten salt-fueled SMR between 500 and 600 MWth (ThorCon)	High-temperature gas-cooled SMR between 200 and 300 MWth (XE-100)	Heat-pipe-based microreactor with power less than 20 MWth (eVinci)
					$10,000 and $20,000/kWe
CREDIT	Onsite construction duration (financial risk)	24 months	10% onsite construction, 24 months	30–48 months for a four-pack	Onsite installation in <30 days
URAN	Fuel type, domestic production	This would depend on the fuel type and whether the fuel can be produced and enriched domestically. For example, some SMR designs may be factory fabricated, but not factory fueled, before shipping to the site for fueling and final installation. Where fuel is sourced from therefore depends on the location of these factories.			MRs may be factory fueled and may not be impacted by domestic uranium production and enrichment capabilities.
Sources:		(NuScale 2022) (Shropshire et al. 2021) (NuScale 2020)	(Martingale Inc. 2015) (IAEA 2022) (IAEA Division of Nuclear Power 2020)	(DOE Office of Nuclear Energy 2021) (Greene 2020) (Brits et al. 2018) (Bragg-Sitton et al. 2020)	(Arafat and Van Wyk 2019) (Westinghouse 2022) (Nichol and Desai 2019)

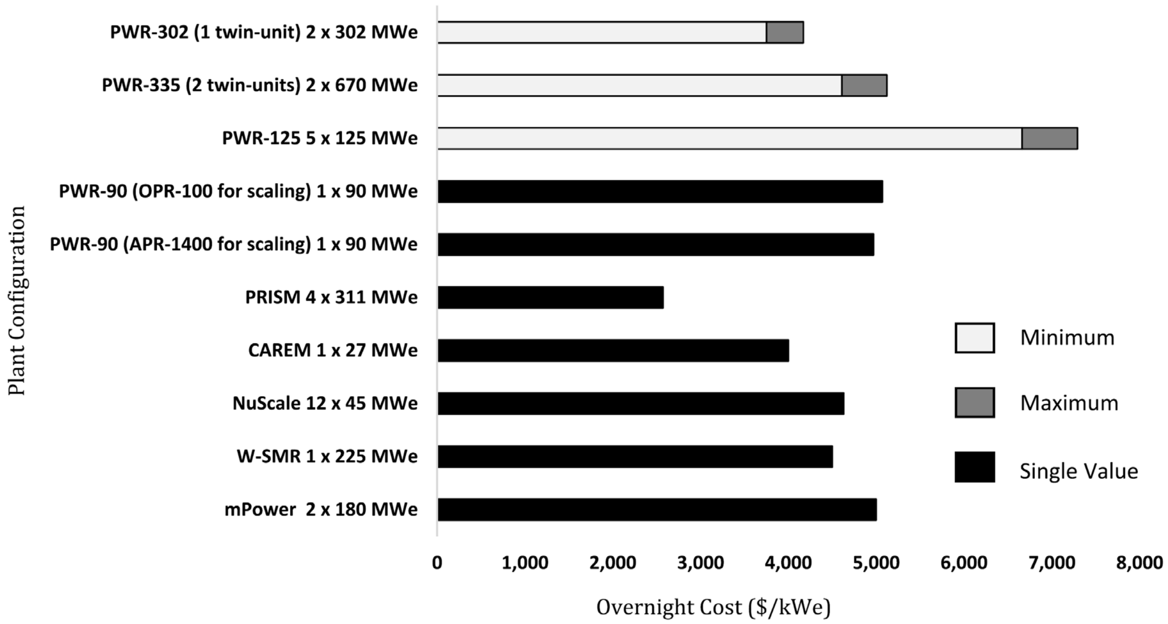


Figure 10. Estimated OCCs for SMRs Source: (Mignacca and Locatelli 2020).

In the following subsections, we discuss the fit of design-specific technical characteristics to the market indicators RES, DESAL, EII, LAND, GDP, CREDIT, and URAN for Brazil. While the designs chosen by EPE are representative of reactor families of interest rather than specific design interest, we present specific design data, when available, to compare across SMR designs. We also include the eVinci technical characteristics for general, non-site-specific comparison between SMR and MR technology, not a design-by-design comparison.

2.3.4.1 NuScale—Water-Cooled Small Modular Reactor

NuScale's water-cooled SMR is a factory produced, transportable (to site for installation) MR. It has target applications for both heat and electricity allowing for integration with grid and industrial applications. Each NuScale Power Module (NPM) has a 77 MWe generating capacity. NuScale offers standard plant solutions in four-module (308 MWe), six-module (462 MWe), or 12-module (924 MWe) sizes (NuScale 2022). Because of the modularity, individual units can be added or removed to meet demand needs. The production of a higher volume of smaller units also allows for greater economies of learning, reducing each subsequent unit's costs. Design simplicity may increase the rate of learning economies. Transporting units from a central manufacturing hub to the utilization site also reduces costs, as it reduces stick-built construction needs, which tend to be the most expensive. Fixed costs (siting, physical infrastructure, environmental impact studies) may also increase less than proportionally, if at all, with each additional unit, further reducing per-unit costs.

There are three main intended applications for the NPM: baseload generation, dispatchable generation, and cogeneration. NuScale's reactors are intended to produce dispatchable baseload energy, which can help smooth generation amounts in accordance with the VRE production levels. This allows for additional utilization of VREs. NuScale's design also does not require external power for safe shutdown and cooling, which adds inherent safety to the reactor. An advantage of each module being independent of other power trains is that demand growth can be met by incrementally adding additional modules. Furthermore, modules can be refueled and serviced independently, without interrupting the output of other SMR modules. For nonelectrical applications that require continuous power, the ability to service and refuel individual modules is beneficial for efficient operation (Ingersoll et al. 2014).

Cogeneration demands, such as desalination, can be met by the NPM's relatively lower temperature process heat (NuScale 2022).

2.3.4.2 ThorCon—Molten-Salt-Cooled Small Modular Reactor

ThorCon is a liquid-fueled, low-pressure, high-temperature SMR. The reactor is designed for simple manufacturing, allowing for increased economies of learning as more units are produced by the same staff. The system provides 557 MWth or 258 MWe with an 80 year overall lifetime and 4 year refueling timeline. Two reactor units are housed in the same silo—but only one operates at a time. The other unit (after operating for 4 years) is allowed to cool for 4 years. This setup allows for uninterrupted power generation as individual units are swapped out every 8 years (4 years of operation, 4 of cooling). EPE is particularly interested in thorium-fueled reactor technologies because of Brazil's rich thorium reserves.

Because ThorCon is a high-temperature reactor, it is expected to have a higher conversion efficiency than low-temperature reactors. The higher thermal output allows the reactor to support industrial applications that other reactors may be unable to integrate with. ThorCon is also purported to have load following capabilities of 5–10% of output per minute between 40 and 100%, allowing the reactor to respond to market conditions or energy user needs. The reactor has an EPZ of 0.5 km and black-start capabilities (the ability to start without external power). The concept has core inlet and outlet coolant temperatures of 565 and 704°C, respectively, (IAEA 2020) and can remain on warm standby island mode in the case of load loss. The reactor has a capacity factor of 90% and thermal efficiency of 46.4%, which is important for EIIs (IAEA 2022). ThorCon's website discusses shoreside applications for the reactor, and it is unclear if it can be used farther inland. With most of Brazil's population living on the eastern coastline, ThorCon's shoreside location may be suitable to serve this population.

2.3.4.3 XE-100—High-Temperature Gas-Cooled Small Modular Reactor

The XE-100 is intended to generate both heat and electricity, either or both for load following baseload energy or industrial applications. Each unit of the reactor is designed for a capacity of 80 MWe, but up to four can be combined for a total capacity of 320 MWe. However, there is technically no cap to the number of reactors, as new units can be added to separate packs. The reactors have a lifetime of 60 years with online refueling capabilities. The reactors utilize tristructural isotropic (TRISO) fuel pebbles with graphite core modulation and have core inlet and outlet coolant temps of 250 and 750°C, respectively. The concept allows for load following operation within the range of 100– 40–100% within 20 minutes (DOE Office of Nuclear Energy 2021). The plant has a thermal efficiency of 42.3% and a capacity factor of 95% (X-energy 2022).

2.3.4.4 eVinci—Heat-Pipe Microreactor

The eVinci heat-pipe microreactor is a nuclear battery designed to produce both heat (up to 600°C or greater) and electricity with load following capabilities. With a capacity of 1–5 MWe, the concept is an MR, with both a smaller capacity and physical size than SMRs. With plans for autonomous operation, transportability, minimal moving parts, and an extremely small EPZ, the MR may be applicable for in-facility energy generation. This opens the design to a significant number of industrial applications, as transportation of heat over long distances incurs significant efficiency losses. The target applications and market for the eVinci MR include remote communities, remote mining operations, military installations, disaster relief, district heating, industrial process heat, and extreme resilience (IAEA Division of Nuclear Power 2020; Valore 2021). Since heat pipes are self-regulated (passive), this enables the eVinci MR to have the inherent ability to autonomously load follow (Arafat and Van Wyk 2019). The eVinci provides operational flexibility through mobility. Before the reactor reaches end of life, it can be transported to a new site (BrucePower and Westinghouse 2021).

2.3.4.5 Relative Concept Applicability for Brazil

RES

- In locations or markets that may need smaller incremental capacity increases, NuScale or XE-100 would provide a better fit than ThorCon, given their smaller installed capacities per module. MRs have smaller capacities than SMRs and thus may serve as a smaller option in providing incremental capacity increases.
- In terms of load following, all three SMR designs are expected provide this capability at varying speeds and output levels. The relative favorability of one design to the next would depend on the market-specific needs. For example, markets with volatile supply and demand may desire an SMR that can provide a larger range in power output. While it is understood that all SMRs must maintain a minimum power output as a percentage of total power output, that percentage may vary across design. Load following speeds, that is ramping up and down power output, varies across designs. Therefore, in certain circumstances, designs with a more agile load following speed may be more attractive.

DESAL

- SMRs with the ability to provide both electricity and heat may benefit markets in need of desalination. As described in Section 2.3.3.2, Brazil has experienced recent challenges with droughts and is forecasted to add a significant desalination capacity (Runte 2016). As such, SMRs with the ability to cogenerate for desalination would be more attractive candidates. While all the designs considered include desalination in their target applications, the reactor coolant outlet temperature varies across designs. NuScale reports a reactor coolant outlet temperature of 321°C, which is the lowest temperature relative to the ThorCon and XE-100 values. X-energy also report that its XE-100 SMR can provide high-quality steam at 565°C. In terms of the thermal capacity available for process heat, NuScale reports that each NPM can provide 250 MWth (the total thermal capacity of each NPM). The eVinci is also designed to provide process heat for desalination purposes. Westinghouse reports a 600°C reactor coolant outlet temperature and 7–12 MWth of thermal capacity available for process heat for its eVinci design.

EII

- EIIs require a reliable power supply for the most economic production. With the push towards decarbonization, industry must also adopt low-emissions sources for production. As such, SMR designs with high-capacity factors are more attractive by providing more resilience to disruption.
- TRL refers to the maturity of a design—the higher the TRL, the closer a concept is to readiness for implementation. NuScale currently has the highest TRL, which is generally beneficial but also specifically beneficial to EIIs. TRL is important to EIIs because:
  - EIIs typically have shorter planning timeframes than electric utilities. As such, high TRLs are desirable as EII decision makers can plan to include SMRs or MRs in their generation mix in the near future.
  - If internal or external decarbonization requirements exist, EIIs are more constrained in potential energy generation technologies, given their requirement for high reliability and, if applicable, a need for combined heat and power generation. Most relevant carbon-neutral generation technologies are variable and would not meet the needs of EIIs without energy storage, which adds to overall costs. If decarbonization goals or requirements have short timeframes, reactor concepts must be at a high TRL to be considered as the replacement generation technology.

LAND

- The indicator LAND is marked Relatively Favorable for SMR suitability in Brazil due to Brazil's high urbanization rate. With less space for dispersed energy systems, Brazil may be more interested in designs that can be sited nearer to or within urban areas. As such, with the smallest EPZs, MRs would be the most suitable system to supply urban populations. The eVinci MR is reported to have a near-zero EPZ and a site footprint of less than <0.5 acres. SMRs generally have bigger EPZs than MRs but smaller EPZs than traditional NPPs. The XE-100 SMR is expected to have an EPZ of 0.4 km and the ThorCon SMR is expected to have an EPZ of 0.5 km or the plant's boundary. NuScale's EPZ is expected to be the size of the site boundary. It is important to note that the ThorCon reactor is specifically designed to be a shoreside reactor.

GDP

- In the context of reactor indicators, GDP is used as a proxy variable for a country's ability to invest in capital-intensive projects. While the CapEx requirements and loan sizes of each concept are not currently solidified, those concepts with smaller CapEx requirements are generally easier to finance. MRs typically have smaller CapEx requirements than SMRs.

CREDIT

- S&P rated Brazil's government bonds as below investment grade, as such, the CREDIT indicator is marked as Unfavorable. Brazil's fitness for investment may increase in the future, however. As such, designs that are less costly and have shorter construction durations would present the least amount of financial risk. Compared to SMRs, MRs are expected to have shorter construction durations and be less expensive to finance. The eVinci MR expects onsite construction duration to be completed in less than 30 days. SMRs are expected to have longer onsite construction durations than MRs. While all the SMR designs are factory fabricated and transportable to site, some onsite construction is still required to get to criticality. The ThorCon SMR estimates 10% of total plant construction to be onsite and is expected to take 24 months to complete. Onsite construction for the NuScale SMR is also expected to take 24 months. The onsite construction duration for the XE-100 is the longest and is expected to take 30–48 months to complete.

URAN

- Depending on the type of fuels and uranium used, Brazil may or may not be able to enrich and manufacture the fuel using uranium from within the country. However, Brazil could potentially send regionally mined uranium to other countries for fuel enrichment and fabrication.

Section 2.3.4 starts by providing a side-by-side comparison of the SMR design-specific technical parameters for the three EPE designs across RES, DESAL, EII, LAND, GDP, CREDIT, and URAN indicators (Table 24). Concept-specific technical specifications do not impact each designs' suitability for all of the 18 IAEA indicators. Only seven indicators differ between design-specific technical parameters. Table 19 also presents eVinci's technical parameters across the same seven indicators. eVinci's information is included to compare the general technologies of SMRs and MRs. Note that eVinci's information included in Table 24 is not meant to be compared with SMRs. Next, Subsections 2.3.4.1–2.3.4.4 briefly introduce each of the four designs designated by EPE. Finally, Subsection 2.3.4.5 compares the technical parameters by design, such as capacity factors or onsite construction duration. For each indicator, we comment and discuss under what circumstances or market conditions specific designs may be a relatively better fit.

2.3.5 Limitations of Methodology and Additional Data Needs

The analysis provided in this section is preliminary in nature and is not intended to recommend any reactor concept for deployment suitability in Brazil. Instead, this report utilizes general indicators to conduct an analysis that can be applied to all reactor concepts across varying market conditions, geographies, and applications in Brazil. Experiential data from SMRs and MRs is limited, and as such, concepts' technical and financial characteristics will become clearer over time. Concepts' favorability under indicators may change pursuant to the updates to these values. Experience with SMRs and MRs may also reveal new indicators not discussed within this report. Microreactor categorization was not conducted due to the lack of regional and local data, which is critically important for applicability analyses. Additionally, the SMR suitability analysis is only relative in nature—between reference countries and reactor types—and does not comment on the absolute suitability of any reactor concept in Brazil.

2.3.6 Discussion and Conclusion

This report explores the suitability of MRs and SMRs in the Brazilian market and also compares expected SMR and MR technology characteristics. While the relative suitability of specific applications, markets, and locations are compared across SMR designs, we only comment on the differences in SMR and MR potential based on technological and financial expectations.

Out of the 18 IAEA indicators, 13 were marked as Relatively Favorable. The two categories in which all the indicators are marked Relatively Favorable are National Energy Demand and Physical Infrastructure Sufficiency. The Brazilian data for the indicators in both of those categories suggest a relatively favorable market for SMR deployment. The favorability of the Brazilian market for SMR deployment is mixed for the other five categories. In the SMR Energy Demand category, both the DESAL and EII indicators are marked Relatively Favorable due to Brazil's forecasted increase in desalination capacity and importance of industry in the Brazilian economy. Due to Brazil's high urbanization rate, the RURAL indicator is marked Relatively Unfavorable. This in terms of cogeneration and use of process heat, Brazilian market data suggests potential applicability.

In the Financial/Economic Sufficiency category, two of the three indicators are marked Relatively Favorable. Due to S&P's current credit rating of the Brazilian government bonds, the CREDIT indicator in this category is marked Relatively Unfavorable. As such, these indicators suggest an ability to invest in SMR and MR technology, although financing may present a challenge. In the Physical Infrastructure Sufficiency category, both the GRID and INFRA indicators are marked Relatively Favorable due to relatively sufficient grid capacity and infrastructure capabilities. The LAND indicator is also marked Relatively Favorable due to Brazil's high urbanization rate. The favorability scores of this category suggest that SMR deployment in Brazil may be a good fit in terms of size, operation requirements, and ability to serve more urban markets.

Two of the three indicators in the Climate Change Motivation category, CO2 and FOSSFUEL/OGC, are marked Neutral. Brazil's NDC and nationwide ten-year energy plans, the country is still interested in increasing the generation of zero and low-carbon energy generation. We mark the NDC indicator as Relatively Favorable.

In the Energy Security Motivation category, the URAN and RES indicators are marked Relatively Favorable, and the ENG IMP indicator is marked Relatively Unfavorable. The RES and URAN indicators are marked as such due to Brazil's plans of large investment in wind and solar capacity as well as the existence of domestic uranium sources that are economically extractable. The ENG IMP indicator is marked Relatively Unfavorable, given the Brazil's relatively lower energy imports. The ENG IMP indicator is marked as such because having relatively lower energy imports creates less of an incentive to ensure domestic needs are undisrupted by external factors.

Commenting on the suitability of MRs in Brazil would require local data and is therefore outside the scope of this report. However, we compared the general potentials of MRs and SMRs to serve certain markets, locations, and applications. Given the expected MR size, applications that may need smaller incremental capacity increase may find MRs more attractive. MRs are also expected to have higher capacity factors than SMRs, making them better suited for markets that desire high reliability. In terms of investment, MRs are expected to cost less and take less time to come online compared to SMRs. Markets or applications with smaller budgets and time-sensitive business models may therefore find MRs a more suitable technology. Furthermore, for business that have shorter decision-making timeframes, MRs provide the flexibility of being mobile. MRs therefore can accommodate riskier or shorter-term business more adequately than SMRs. Lastly, with smaller EPZ requirements, MRs may have to ability to be sited closer to urban areas than SMRs. Countries with high urbanization rates may then consider MRs for options beside rural or remote locations.

This work is a preliminary, non-site-specific, non-design-specific analysis of SMR and MR deployment in Brazil. Future work would require a selection of potential sites and designs to analyze the suitability of these technologies in specific use cases. This is especially the case for MR deployment analysis. Given the size and expected technical characteristics of MRs, local data would allow conclusions to be made on MR deployment suitability. As technical and financial parameters become clearer, results and conclusions can be updated accordingly.

2.4 Outcome 4: Identify Licensing- and Safety-Related Cost Reduction Opportunities

2.4.1 Regulatory Framework Review

INL staff reviewed the regulatory procedures (translated via Google Translate) identified by EPE to understand the regulatory structure of the Brazilian nuclear program. These included procedures related to the control and protection of nuclear materials, environmental regulations, licensing of nuclear facilities, quality assurance, in-service inspection, and siting. Currently, Brazil is in the process of a restructuring of its nuclear regulator, Comissão Nacional de Energia Nuclear (CNEN), and new personnel have not been identified as the points of contact for the regulatory procedures. Therefore, INL staff were unable to meet with the Brazilian regulators to discuss potential structural changes that would provide a similar level of protection to public safety and security but reduce the overall cost of licensing and regulations. This task will be performed pending a Phase Two of this project being developed and funded as well as the identification of relevant staff in the new Brazilian nuclear regulatory agency.

2.4.2 Procedure Reviews

The review of NE 1.01, “Licensing of Nuclear Reactor Operators,” resulted in a robust operator training program with requirements that provided a thorough program for the licensing of nuclear operators. The procedure also covered testing, requalification, qualification suspension, and other program requirements. INL staff does not recommend any changes to this procedure.

The review of NE 1.04, “Licensing of Nuclear Facilities,” resulted in a robust licensing process for nuclear facilities in Brazil. This procedure contained the licensing processes for Approval of the Site, Construction License (total or partial), Authorization for the Use of Nuclear Materials, Authorization for Initial Operation, Authorization for Permanent Operation, and the Cancellation of Authorization for Operation. It specifies what the Preliminary Safety Analysis Report and Final Safety Analysis Report must contain to be considered complete and used in an application as well as when they are required during the licensing process. Section 6.5 describes the acceptance of codes and technical standards in the design and construction of the reactor. One possible update would be to include American codes and standards organizations by name as many of the designs that Brazil will review will be designed to those codes and standards. This procedure also includes the requirements for Emergency Planning and Technical Specifications. INL staff would recommend the development of technology-inclusive, risk-based regulations for the licensing of nuclear facilities. It is anticipated that many American companies will design using a risk-based path that focuses on the use of a probabilistic risk analysis.

The review of CNEN NN 1.16, “Quality Assurance for the Safety of Nucleoelectric Plants and Other Facilities,” resulted in a satisfactory and robust quality assurance program that can be implemented to ensure nuclear quality. INL staff noted that CNEN requests quality assurance documents be written in Portuguese unless otherwise impractical. CNEN’s insistence on the verification of translated documents provides significant assurance that the document can be reviewed and utilized with accuracy. The review showed significant similarities to 10 CFR Part 50 Appendix B and ASME NQA-1, which indicates a robust and highly functional quality assurance program.

The review of NE 1.20, “Emergency Cooling Water Systems,” resulted in robust emergency cooling water system requirements that cover all phases of emergency operations. However, INL staff recommend updating the emergency cooling water system requirements to cover other reactor technologies. While these requirements are satisfactory for LWRs, they do not support other reactor technologies, such as HTGRs, MSRs, or FRs. Developing regulations for these types of technologies will be critical depending on the reactor technologies selected for Brazil.

The review of the NE 1.21, “Maintenance Standard,” resulted in a robust maintenance program, with requirements that provided broad and performance-based qualitative requirements for the establishment and operation of an NPP maintenance program. INL staff recommend an update to the considerations for administrative controls and procedures for the preparation of maintenance documents in Section 6.2. Licensees should consider the necessity for breathable air. Several advanced reactor vendors plan to use spaces with inert atmospheres for the control of combustion and fires. Maintenance personnel would need breathing apparatuses or the ability to flush the area with breathable air and test oxygen levels prior to entry and beginning work. In addition, there should be a consideration to working condition and equipment temperature. Several advanced reactor vendors will be using high temperature working fluids (e.g., gas, sodium, salts) that could produce working condition hazards for maintenance crews and should be accounted for in maintenance planning.

Standard NE 1.22, “Support Meteorology Programs and Nucleoelectric Plants,” contains prescriptive and performance-based requirements for the meteorological monitor programs and equipment for a NPP. INL staff recommends an update to Section 5.2.2, which provides prescriptive requirements for wind speed measurements. The prescribed elevations may not provide appropriate data for smaller and near-field deposition radionuclide releases expected from ARs. A revision of this standard that allows an alternative height to 60 meters that more closely matches the probable atmospheric release height would provide flexibility to advanced reactor designs. Current work in the United States related to near-field radionuclide dispersion models for ARs would provide analysis tools to justify wind monitoring elevations for plant sites.

Standard NE 1.25, “In-Service Inspection at Nucleoelectric Plants,” details the programmatic requirements of the preservice and in-service inspection programs. The standard is unclear on the scope of the in-service inspection program and does not clearly require those items that are important safety items and/or reactor refrigerant pressure barrier boundaries. A note for ARs is that the concept of the reactor coolant pressure boundary may not be applicable to all designs, though many use a working fluid. Additionally, many AR designs use the concept of functional containment that uses a single or several barriers (to include the reactor coolant pressure or fuel boundary) that “effectively limit the physical transport and release of radionuclides to the environment across a full range of normal operating conditions, AOOs, and accident conditions” (U.S. NRC Functional Containment). Revisions to the preservice and in-service inspection program to appropriately address fission product barriers and those AR systems important to safety may be beneficial to advanced reactor vendors.

Standard NE 1.26, “Safety in the Operation of Nucleoelectric Plants,” details a breadth of programmatic requirements for NPP operation. Standard 1.26 would require no updates to accommodate an advanced nuclear reactor.

Standard NE 1.27, “Quality Assurance in the Acquisition,” Project and Manufacturing of Fuel Elements details programmatic elements to be addressed in a fuel quality assurance program. Standard 1.27 would require no updates to accommodate advanced nuclear reactor fuel.

Resolution 09/69, “Rules Choosing Places for Installation of Power Reactors,” provides requirements for the siting and establishment of exclusion zones and low population areas for NPPs. This resolution would require no update to accommodate advanced nuclear reactors that would be anticipated to have lower risk and inventory associated with possible accidental releases and also be placed closer to population centers.

Standard NE 2.02, “Control of Nuclear Materials,” provides the specific program requirements for a Material Control and Accountability Program for fissile material to include nuclear reactor fuel. Standard 2.02 provide requirements that would be applicable to advanced nuclear reactor fuel to include storage, handling, and import and export of fuel.

Standard NE 2.03, “Protection Against Fires in Nucleoelectric Plants,” provides the programmatic requirements for a fire protection program at an NPP. Standard NE 2.03 could use an update to address the possibility of more exotic materials in advanced nuclear plants that would require alternative firefighting methods. Some advanced nuclear reactors plan to use molten sodium, which explodes upon exposure to water due to the quick formation of hydrogen gas and sodium hydroxide. In addition, the use of fuel-bearing molten salts upon contact with water would lead to the rapid transport of fission products. Standard NE 2.03 Section 12 should include greater considerations for the selection of firefighting equipment to be appropriate to the materials located onsite and to be aligned with the safety goals of the facility design.

Standard NE 5.02, “Transport, Receipt, Storage, and Handling of Fuel Elements of Nucleoelectric Plants,” provides the specific requirements for fresh and spent fuel at a nuclear power reactor. Standard NE 5.02 requires updates to accommodate the anticipated fuel types for advanced nuclear reactors, specifies that fuel elements contain fuel rods, and needs to be updated to reflect other physical fuel circumstances (to include fuel element handling equipment and tools and requirements for damaged fuel elements). Standard NE 5.02 otherwise is applicable to the increased enrichments, fuel forms, and fuel elements expected from advanced nuclear reactors.

2.4.3 Reactor Design Analysis

EPE staff selected four reactor categories as their likely candidates for further evaluation based on modularity and readiness for deployment. INL staff are currently working with Department of Commerce staff to hold a workshop for all interested reactor vendors. This workshop will help INL and EPE determine the modularity of designs, designers' interests in developing in Brazil, estimated supply chain needs, and a timeline from groundbreaking to power ascension testing. These aspects will be critical to the Brazilians selection of reactor vendor(s) for development. Should a Phase Two be proposed and funded, INL staff will work with the interested reactor vendors and Department of Commerce staff to determine modularity of designs, supply chain details for Brazil, and a timeline from groundbreaking to power ascension testing.

2.5 Outcome 5: Evaluate the Broader, Longer-Term Trade-Offs for Using Small Modular Reactors

The contemplation of the long-term *lifecycle economic* trade-off of any SMR technology must be made, among many factors, within the context of the overall Brazil energy policy objectives, energy demand, and source energy mix. Many of the factors affecting that contemplation are provided in preceding sections of this report.

In addition to the longer-term economic trade-offs of a given SMR technology, there are the practical issues of radioactive waste (RW) and spent nuclear fuel (SNF) management, and eventual reactor decommissioning. While waste management and decommissioning costs are and can be broadly accounted for by various funding mechanisms (e.g., waste management fees tied to power generation, RW volume, SNF mass, etc.), there are aspects of both waste management and decommissioning that are unique to the SMR technology in question and that should be better understood before selecting a preferred SMR technology.

The four SMR technologies selected for this report represent a very broad range of reactor design and fuel concepts. Some of the reactor designs, fuel forms, and reactor operational constructs are more defined than others and are more applicable to prior experience than others. Consequently, most commentary herein on RW and SNF management and decommissioning strategies should be taken as presumptive or speculative. Logically, as each SMR technology progresses beyond an initial conceptual design phase to full reactor design engineering and onto reactor and plant design licensing and certification (necessary for commercialization), greater resolution regarding the RW and SNF management and reactor and site decommissioning should be expected.

As noted in República Federativa do Brasil (2017), World Nuclear Association (2021), and IAEA (2021), CNEN is responsible for RW management and disposal. Legislation in 2001 provides for repository site selection, construction, and operation for low- and intermediate-level wastes, a solution for which is to be in place before Angra 3 is commissioned. The policy and strategy for SNF management beyond interim storage, whether reprocessing or direct disposal, is still pending technical, economic, and political decisions (República Federativa do Brasil [2017], Section G.7.1).

Irrespective of the SMR technology, Brazil has an established:

- RW management policy (República Federativa do Brasil (2017), Section B – Policies and Practices, B-1 – Introduction, Paragraph 2)
- Waste classification system (República Federativa do Brasil (2017), Table B-1 – Waste Classification)
- General safety regulations and requirements for the management of RWs, including those arising from reactor operations (República Federativa do Brasil [2017], Section H.1 General Safety Requirements).

The potential RW and SNF management expectations and possible reactor and site decommissioning expectations are discussed below in the context of international experience and currently established policy and practice in Brazil and of specific SMR technology considerations.

2.5.1 Radioactive Waste Management

RW management is discussed generically as most reactor technologies have some small quantities of variously gaseous, liquid, and solid radioactive wastes arising from their routine operation. In this discussion, RW management considerations are limited to the solid wastes generated from routine operations; that is the low- and intermediate-level waste (LILW) anticipated for near-surface disposal.

The same waste classification and dosed-based regulations (limiting dose to workers and the public and releases to the environment) are assumed to be equally applicable to any licensed SMR technology. Likewise, for temporary RW storage, the waste management practice could be assumed to be similar to existing practice though the actual waste burden (radionuclide quantity, volume, form, treatment, and conditioning) would depend on the SMR technology in question. As an example, the NuScale SMR would likely generate a waste management burden most similar to existing LWR installations, such as Angra 1 and 2, while other SMR technologies involving molten-salt- or TRISO-fueled reactors could generate less certain volumes of LILW. Regardless, the broad international experience with RW forms generated from a diverse set of existing non-LWR technologies suggests the safe temporary storage of a variety of LILW forms can be readily achieved, including more challenging ones, such as irradiated graphite.

However, regarding the permanent disposal of LILW forms in a near-surface disposal facility, greater care should be exercised in assuming compatibility between future LILW waste that is different from currently generated LILW and the not-yet-developed near-surface disposal facility. Brazil has initiated the *RBMN Project* (Republica Federativa do Brasil [2017], Section K.2.1 The Brazilian National Repository) to site and eventually develop a disposal facility for the LILW inventory now placed in temporary storage. A future disposal system (IAEA [2014]) is a reflection of, among other factors, the physical facility design, the local geologic conditions, the regulatory framework (e.g., period of containment, release limits), the waste acceptance criteria, and the expected waste inventory. The LILW disposal facility now being conceived for Brazil would naturally reflect the existing RW inventory and that projected from continued operations: "The design concept will be a near-surface multi-barrier repository constructed in compliance *with the currently existing waste inventory and the radioactive wastes that will be generated in the future*" (emphasis added, Republica Federativa do Brasil [2017], Section H.3.2, Low and Intermediate Level Waste Repository). Caution is advised in assuming the LILW arising from the deployment of SMR technologies with characteristics different from existing LILW generation will be acceptable for disposal, especially when neither the anticipated LILW characteristics or the disposal facility design are adequately specified.

In summary, the LILW radioactive waste (appropriate for near-surface disposal) arising from routine operations of most any SMR under consideration can confidently be assumed to be appropriately managed for temporary *storage*. The specific treatment, conditioning, and packaging necessary would reflect the LILW waste form characteristics. While numerous examples of LILW waste *disposal* facilities exist, the engineering design, construction, and cost, of a given facility is largely dependent on many presently uncertain factors (e.g., waste characteristic, local geology, disposal criteria). More detailed understanding of the waste form and proposed disposal system is required to evaluate waste acceptance criteria compatibility for ultimate disposition in a near-surface disposal facility.

2.5.2 Spent Nuclear Fuel Management

Several terms are used to describe post-irradiated fuel forms or their post-reprocessing form, arising from various reactor technologies, including SNF, fuel salt, high-level waste, and fuel particles. For this discussion, the term SNF broadly includes both typical LWR fuel rod assemblies and less common post-irradiated fuel forms arising from molten-salt fuels, TRISO pebble fuels, etc.

All SNF management starts at the reactor facility, typically in a temporary storage configuration, and a complete SNF management strategy will result in final disposal. Geological disposal is the end point of virtually every SNF management strategy, whether the strategy involves interim storage, transport, conditioning, or reprocessing as an intermediate step.

In the case of Brazil, the long-term SNF management strategy was a concern, as noted in República Federativa do Brasil (2017) Section G.7.1, Fuel from NPPs:

> The decision regarding reprocessing or disposal of spent fuel has not been taken in Brazil. The current policy adopted in Brazil with regard to spent fuel is to keep it in safe storage until a technical, economic and political decision is reached about reprocessing and recycling the fuel or disposing of it as such. It should be emphasized that, by the Federal Brazilian Law, spent fuel is not considered as radioactive waste.

This concern was addressed in 2017 when Brazil signed a turnkey contract with Holtec International for a dry storage facility that would hold spent fuel from Angra 1 and 2. The Angras Complementary Dry Storage Unit for Spent Fuel will have the capacity to store used fuel until 2045 (World Nuclear News 2021).

2.5.2.1 Disposition Options

A set of options was developed for the disposition of research reactor spent fuels (IAEA 2021b) but equally illustrates a framework for the disposition of current and future power reactor spent fuels. Adapted and summarized below, the options broadly include intermediate combinations of storage, conditioning, and reprocessing, before final disposition by emplacement in a presumed deep geologic disposal facility.

Option 0: On-reactor-site storage. This is essentially the “do nothing” option and is not suitable for long-term storage.

Option 1: Direct disposal. This involves moving the spent fuel directly from the reactor pool storage to the final disposal facility.

Option 2: Conditioning, storage, disposal. Fuel is sent from the reactor pool to be conditioned (e.g., structural parts are cut to minimize waste volume, fuel assembly is encased in a stabilizing container or matrix), then placed in away-from-reactor storage before being sent to the final disposal facility.

Option 3: Storage, conditioning, storage, disposal. This is the same as Option 2; however, there is an additional storage period prior to conditioning.

Option 4: Storage, direct disposal. Fuel is moved from the reactor pool, placed in storage away from the reactor (wet or dry), then moved to final disposal.

Option 5: Storage, reprocessing, storage, disposal. Fuel is moved away from the reactor facility into storage away from the reactor (wet or dry), then taken to a reprocessing facility. The waste product from reprocessing is then moved to a storage facility away from the reactor before disposal.

Option 6: Reprocessing, storage, disposal. This is the same as Option 5, except the fuel is moved directly from the reactor into the reprocessing facility.

Option 7: Fuel return. Fuel is returned to the country of origin (i.e., the country where the nuclear material was enriched), which takes responsibility for the final disposal.

Option 8: Conditioning, disposal. Spent fuel is conditioned prior to placement in the final disposal site. It is the same as Option 2, except there is no storage after conditioning.

Option 9: Storage, conditioning, disposal. Fuel is moved away from the reactor facility, stored, then moved to a conditioning facility prior to the final disposal. It is the same as Option 3, except there is no storage after conditioning.

Option 10: Storage, reprocessing, disposal. This is the same as Option 5, except there is no storage after reprocessing.

Option 11: Reprocessing, disposal. The fuel is moved directly from the reactor facility to a reprocessing facility, then the waste product from the reprocessing is moved directly to the final disposal site. It is the same as Option 6, except there is no storage after reprocessing.

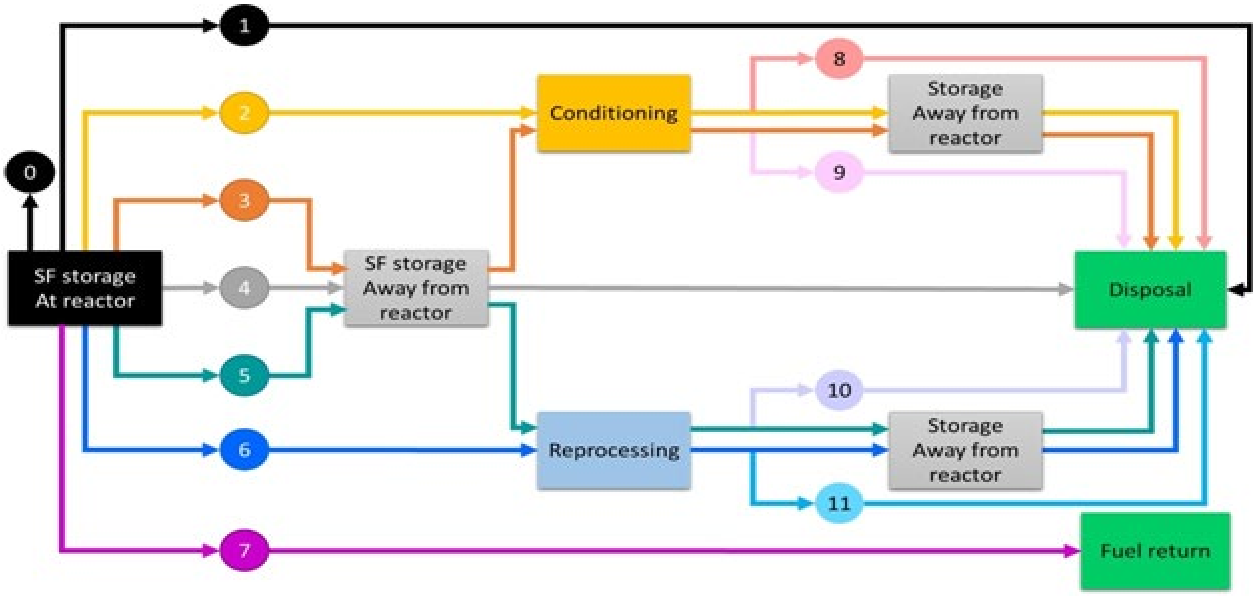


Figure 11. SNF management options (adapted from IAEA [2021b]).

It is noted that, while research reactor SNF return (i.e., Option 7 above) has been practiced globally, including shipments from the Brazil IEA-R1 reactor to the U.S., this option cannot be assured for power reactors without considerable government-to-government negotiation prior to final decisions on a spent fuel management strategy. Similarly, the procurement of spent fuel reprocessing services from foreign suppliers has been exercised but is understood to involve the return of some quantity of RW requiring deep geologic disposal domestically.

2.5.2.2 Small Modular Reactor Spent Nuclear Fuel Disposition

Except the NPM, most SMR designs under evaluation are only now entering prelicensing regulatory engagement discussions in anticipation of formal regulatory reviews for design certification (e.g., 10 CFR Part 52 Subpart B in the case of the U.S. NRC). With reactor design certification being focused on reactor safety, detailed spent fuel management plans are not expected until licensing for site-specific deployments (e.g., 10 CFR 52 Subpart C in the case of the U.S. NRC) wherein the temporary SNF management practice is defined in more detail.

As such, the level of detail on presumed spent fuel management for each SMR technology is varied and largely drawn from multiple reactor vendor marketing material or technical presentations (as opposed to site-specific construction and operating licensing documents) and is understandably muted on issues of disposal. For transportation and storage considerations, additional insights were drawn from a recent report of advanced reactor waste management concepts (DOE Office of Integrated Waste Management 2022, draft), which examined classes of reactor fuel forms (e.g., LWR, MSR, TRISO, metallic) and several specific reactor design concepts.

With regard to considerations of ultimate disposition in a deep geologic disposal facility (IAEA 2011), the overall objective is to contain and isolate the waste from the accessible environment for long time periods, wherein the safety of the disposal facility is intended to be provided by passive means inherent in the characteristics of the site design and waste. Siting of a deep geologic disposal facility depends on a great number of considerations (e.g., thermal loading, geo-hydro-chemical environment evolution, radiological and nonradiological waste form characteristics and quantity, disposal regulations and performance criteria, stakeholder acceptance). As few of these considerations can be described in detail, particularly for novel SMR fuel forms, any forecast of geologic disposal feasibility in Brazil would be speculative, notwithstanding Brazil's current efforts to address the SNF from the Angra reactor fleet, which is pending policy decisions toward reprocessing or direct disposal.

NuScale

The SNF from an NPM is expected to be very similar to most existing LWR SNF other than being half-height assemblies with distinct fuel enrichment and burn-ups. When removed from the core, SNF is stored in the fuel pool inside the reactor building for cooling for at least 5 years. The NuScale design includes an integral steel-lined concrete pool with a capacity for the accumulation of spent fuel assemblies (plus temporary storage of new fuel assemblies) for up to 10–15 years. After cooling in the spent fuel pool, spent fuel can be placed into certified casks onsite. The NuScale's standard facility design includes an area for the dry storage of all of the spent fuel for the 60-year life of the plant (Figure 12).

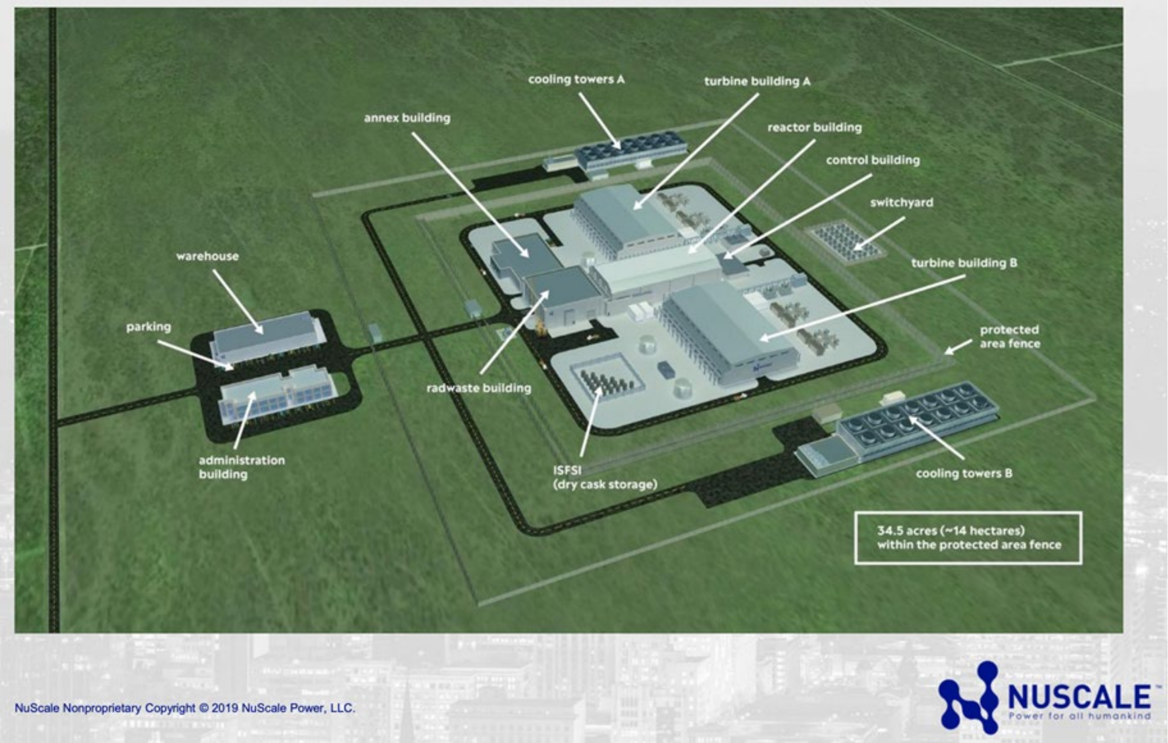


Figure 12. NuScale facility layout—note dry cask storage in southeast corner.

Other than the possibility of modified dry cask storage system designs to accept half-height spent fuel assemblies, the anticipated dry cask storage system would be very similar to that now in existence for the Angra reactor spent fuel discharges (Figure 13).


Figure 13. The onsite used fuel dry storage facility at Angra (Image: Holtec International).

Actual disposal experience with typical LWR SNF and associated high-level waste is pending the design, licensing, construction, and operation of several deep geologic disposal facilities now in progress in multiple countries, with a substantial technical basis from decades of research and development (Nuclear Waste Management Organization 2020).

X-energy XE-100

Principal characteristics of the X-energy XE-100 design that can affect the eventual SNF management are the use of TRISO particles with high-assay low-enriched uranium enrichment (~15.5%), continuous refueling, and anticipated high burn-up (~165 GWd/MT). As noted elsewhere in this report, there are several international examples of "pebble-bed" test and research reactors in various stages of development. In all cases, the discharged spent fuel is placed in appropriate spent fuel casks for storage pending final disposal.

As noted in Department of Energy (DOE) Office of Integrated Waste Management (2022) and IAEA (2020), for the XE-100 design, upon arrival at the plant, the fuel handling system moves fresh fuel pebbles to the reactor where they remain until the fuel has been fully utilized. The pebbles are then removed from the reactor and transferred to the spent fuel storage system and deposited into spent fuel casks. The casks are stored onsite for the life of the plant, nominally 60 years.

As yet there is no disposal experience with spent TRISO fuel particles, though several technical evaluations by Hall (2019) and Gelbard (2018) suggest that repository performance could be orders of magnitude better than for LWR SNF because of the chemical characteristics of the spent coated particle fuel (e.g., protective SiC layer), albeit requiring more waste package volume owing to the larger fuel-to-volume ratio compared to LWR SNF.

ThorCon

As a proposed ship-borne molten-salt fuel reactor station, the spent fuel (spent salt) management is somewhat unique. As with most MSR fuels, the fission products are expected to be bound in the salt, which is drained to a holding tank for cooling and solidification while maintaining a subcritical configuration.

The ThorCon design purports the used fuel salt would be stored in a cooldown can in a passively cooled secure silo while initial fission products decay. After some years of storage, a visiting CanShip exchanges casks of used and fresh fuel salt. The design concept anticipates spent fuel salt reprocessing, returning the cans of spent fuel salt to a centralized recycling facility and fuel casks to a separate fuel handling facility. ThorCon asserts the power plant can store up to 80 years of used fuel onboard, using passive air cooling, and that one 3 m diameter cask would be sent to storage every four years (Figure 14).

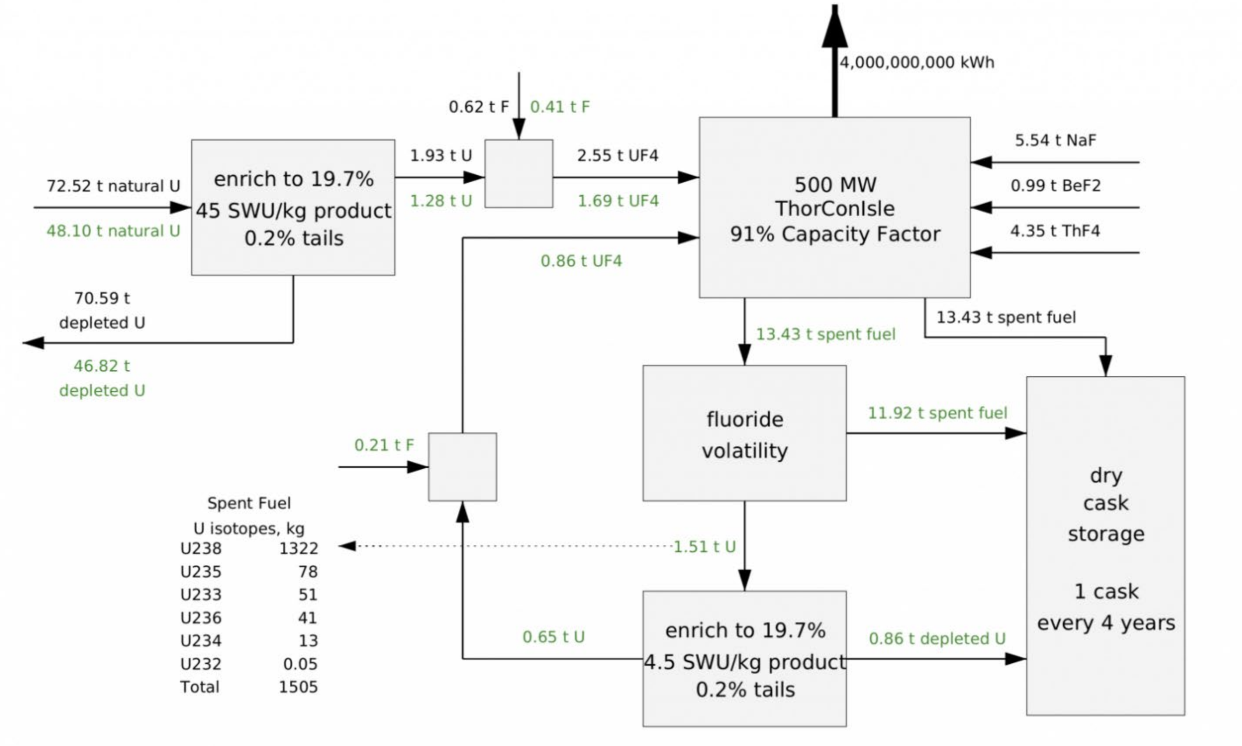


Figure 14. Annual 500 MW ThorCon fuel cycle flows in tonnes, averaged over 8 years. Source: ThorCon website.

The material balance and waste generation presented in Figure 14 has not been independently assessed, either with or without reprocessing. A thorough review of spent molten-salt fuel for several MSR designs, including fluoride and chloride fuel salts, is provided in DOE Office of Integrated Waste Management (2022), Section 2.2.

Irrespective of the assumed spent fuel burden suggested by ThorCon, the feasibility and issues surrounding fuel take back schemes (i.e., Option 7 in Section 2.5.2.1) for reprocessing or final disposition should not be taken for granted as a national spent fuel management strategy.

Westinghouse eVinci^{TM} Microreactor

The eVinci is envisioned as a self-contained, transportable "nuclear battery," purportedly with a core that might use high-assay low-enriched uranium in a TRISO fuel or other encapsulated fuel form. Westinghouse has suggested the U.S. NRC licensing review of the eVinci design could be more appropriate under established guidelines for non-power (research or test) reactors (Westinghouse Electric Company 2021). Whether licensed as a power or non-power reactor can affect the regulatory requirements applied and long-term management strategy, in both the U.S. and Brazil.

The eVinci microreactor is designed for a 3+ year operation cycle, whereafter the entire device, being deployed in a standard shipping container, is disconnected and transported "back to the factory in its original canister for refueling and redeployment or long-term storage" (IAEA 2020). In this regard, there is presumably no management burden of RW from routine operations or with spent fuel disposition. However, as with other designs that anticipate "fuel return," the feasibility and issues surrounding fuel take back schemes (i.e., Option 7 in Section 2.5.2.1) should not be taken for granted as a national spent fuel management strategy until government-to-government agreements are concluded.

2.5.3 Decommissioning

All site-built nuclear power stations, including SMR designs such as the NuScale and XE-100 designs, are eventually subject to decommissioning decisions. Under the established decommissioning regulatory framework of Brazil (Comissão Nacional de Energia Nuclear 2017), decommissioning strategies can include immediate or delayed dismantling of the plant or possibly containment (also known as entombment). As with most decommissioning strategies, the financial resources are amassed through a ratepayer tariff structure. In the case of Brazil, financial management is a part of the regulatory framework (Comissão Nacional de Energia Nuclear, 2017) and addresses the management of RW generated during decommissioning. As the Brazilian long-term spent fuel management strategy is undecided at present, it is presumed that the technical and financial decommissioning requirements include a provision for implementing an interim dry cask storage system.

At present, preliminary plans presenting two alternatives (presumably immediate and delayed) have been drafted for the future decommissioning of Angra 1, 2, and 3, with reference costs of ~$500 million per unit (República Federativa do Brasil 2017, pgs. 61 and 78). The Brazil decommissioning approach established for the existing reactor units at Angra would be readily applicable to other site built SMR reactor stations, such as the NuScale. Applicability to the XE-100 design should be evaluated, recognizing the international experience with "pebble-bed" reactor decommissioning is limited.

Decommissioning strategies are intended to restore all sites sufficiently to exit regulatory control. While the RW and SNF management aspects are purported to be minimal with the eVinci transportable reactor and ThorCon floating reactor designs, applying the existing Brazil decommissioning regulatory framework to the novel designs such as would need to be evaluated for adequacy.

3. CONCLUSIONS AND NEXT STEPS

In support of the U.S. DOE, INL collaborated with EPE to perform a technology, economic, and regulatory analysis of SMRs, ARs, and MRs. The analysis documented in this report provides information to assist Brazil's policy making and long-term energy planning, whose official indicative scenarios show an increase in operating nuclear power, from 2 GW in 2022 to 8–10 GW by 2050. The NPP Angra 3, under construction, is expected to start operation in 2027 with 1.4 GW of installed capacity.

The information assembled in this report is aimed at supporting decision-making for future nuclear power investments and helps to consider questions such as:

- What types of nuclear power technologies may support the market for nuclear construction under consideration in Brazil?
- How would modular nuclear technology assist in the deployment of nuclear energy in Brazil?
- What are the Brazilian supply chain issues for nuclear power deployment?
- What does the regulatory landscape look like for licensing of advanced nuclear reactors in Brazil?

In addition to the information gathered in this initial phase of the project, we have several recommendations for next steps to consider for future activities:

- A roundtable for U.S. technology opportunities in the four Brazilian reactor categories of interest identified in the project should be considered. This roundtable will serve to identify and highlight U.S. technologies and companies that can serve a role in deploying future nuclear power options in Brazil.
- A deeper dive into available U.S. government tools (e.g., design, manufacturing, finance) to obtain a richer detail of options available to Brazil.

- Expand and further refine the TRL concepts used in the initial scoping aspect of the project.
- Track changes in the technology space, including licensing and design aspects, and update the report as needed.
- Engage with the new nuclear regulator in Brazil (once in place) and seek a joint licensing concepts workshop to discuss U.S. approaches to AR regulation and licensing.
- Evaluate the technical possibilities of coupling nuclear energy to markets other than electricity, such as industrial process heat, hydrogen production, and desalination, and the corresponding economy of scope in Brazil.

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Appendix A
SMR Characteristics and Comparison with Large Reactors

The IAEA provides a helpful overview of SMRs characteristics and a comparison with large reactors (LRs) (IAEA 2022). These factors include:

1. Factory Fabrication

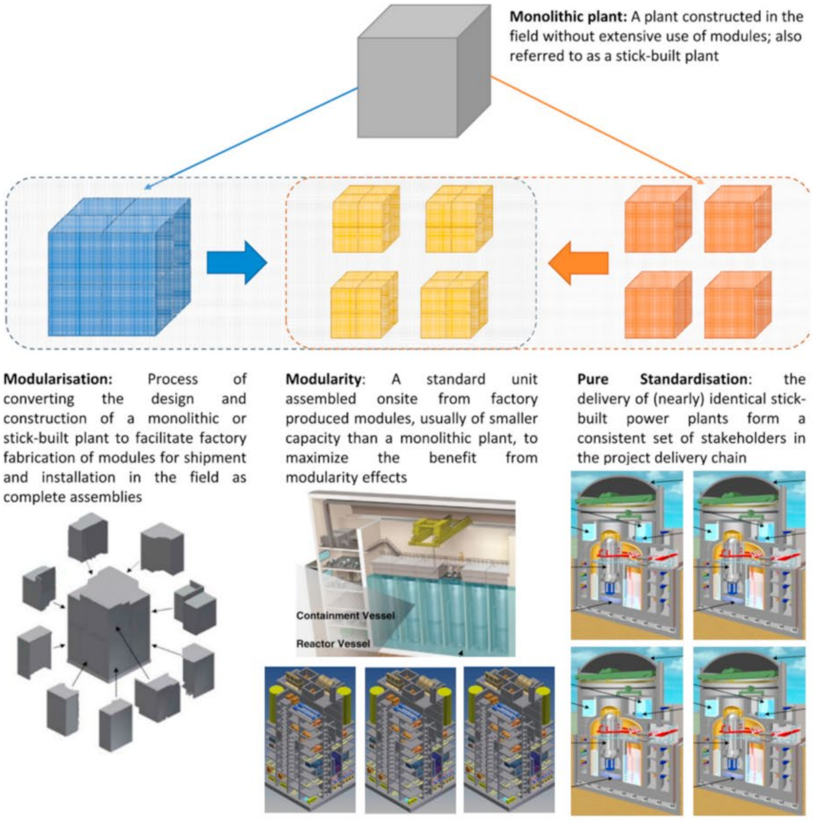
   LRs typically have components manufactured offsite and shipped and assembled onsite. Significant amounts of construction occur onsite, which generally requires relocation of large, temporary high- and low-skilled labor forces – often at significant cost. SMRs may reduce construction requirements and costs with smaller sizes and EPZ.

2. Learning Economies

   Experience with a process can increase manufacturing efficiencies, reduce costs, and shorten production times. If individual SMR concepts are produced in a factory setting, each subsequent unit can experience cost reductions in comparison to the prior. Because of the smaller capacity, lower overall cost, and higher expected adoption of SMRs compared to LRs, it is expected that learning economies will benefit smaller reactors more than larger. Multiple factors play into this potential phenomenon, as more units could be produced more quickly, in a factory setting, with the same workforce, which is expected to increase learning rates and thus decrease costs relatively quickly.

As learning economies (among other factors) reduce costs with the production and operation of more units, overall costs move from first-of-a-kind (FOAK) to NOAK (Boldon and Sabharwall 2014).

3. Modularization, Modularity, and Standardization



Monolithic plant: A plant constructed in the field without extensive use of modules; also referred to as a stick-built plant

Modularisation: Process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies

Modularity: A standard unit assembled onsite from factory produced modules, usually of smaller capacity than a monolithic plant, to maximize the benefit from modularity effects

Pure Standardisation: the delivery of (nearly) identical stick-built power plants form a consistent set of stakeholders in the project delivery chain

(Top) Definitions of Modularisation, Modularity and Standardisation (Mignacca and Locatelli, 2020). Partitioned large nuclear steam supply system (left, AP1000), Nuscale combined integrated modules (middle top, Ingersoll et al., 2014), integrated Westinghouse SMR NSSS modules (middle bottom, Maronati et al., 2018b) standardisation see Hanul Nuclear Power Plant (AB1600 plant in right picture (Arai et al., 2008)).

Figure 15. Modularization, modularity, and standardization.

Fabrication tends to be less expensive when parts are manufactured offsite and then shipped to the site for installation. A rule of thumb estimation showing the differences in costs for fabrication strategies is the “1-3-8” rule, where what costs $1 to factory manufacture costs $3 and $8 in assembly areas and stick builds, respectively (Maronati et al. 2018).

Modularization – As shown in Figure 15, modularization involves the fabrication of reactor parts offsite and installation onsite. This allows the efficiencies of factories to reduce cost and fabrication time.

Standardization – As shown in Figure 15, standardization involves utilizing the same design for multiple constructions, reducing costs by allowing for learning economies and reducing costs for repairs and replacement.

Modularity – Together, modularization and standardization create modularity, which benefits from the cost reductions of each constituent part.

Modularity has two meanings in reference to SMRs: "(1) a single reactor that can be grouped with others to form a large nuclear plant, and (2) whose design incorporates mainly prefabricated modules assembled on site" (Locatelli, Bingham et al. 2014). Modularity (definition one) is desirable because of co-siting effects, (adding more units does not increase cost linearly because of shared costs like siting, regulation, and balance of plant), and because investment can be staggered, (individual units purchased over time, as opposed to the construction of one or a few LRs), decreasing risk and allowing for proportional responses to market characteristics. Other benefits (definition two) decrease costs because offsite manufacturing tends to be less expensive than onsite.

4. Reduced Lead Time

   Because of shorter manufacturing, construction, and installation times, SMRs have a shorter lead time than LRs, which can take many years to be constructed. A shorter lead time reduces risk for the purchaser because market characteristics have less time to change and potentially become less ideal for nuclear applications.

5. Transportability

   As compared to some microreactor or fission battery concepts, SMRs are generally permanently stationed once installed. However, significant parts or entire units can be transported from manufacturing facilities to the installation site. This reduces the amount of work required onsite and, thus, costs.

6. Size Considerations – Footprint and EPZs, Locational Flexibility

   SMRs are physically smaller than LWRs and require less material overall, leading to overall cost reductions – although the smaller capacity leads to diseconomies of scale per kW capacity as compared to larger reactors. "An EPZ is the area in the vicinity of a NPP for which detailed plans are implemented for the management of emergencies and for the communication of the risks of nuclear energy production" (Giordano, Anderson et al. 2010). Depending on regulatory decisions, SMRs may have EPZ, allowing more flexibility in siting and lower costs than larger reactors.

7. Safety Features

   With relatively poor public perception of nuclear, a central aspect of developers' targets is to present a strong safety case of SMRs over traditional-scale LRs. SMR concepts aim to provide enhanced passive safety features compared to conventional scale LWRs.

8. Reduced Staffing

   Because of their relative simplicity and smaller size, SMRs will require fewer staff than LRs. However, this factor may also experience diseconomies of scale and require more staff per kW capacity than LRs.

9. Integrated Energy Systems

   While not necessarily unique to the technology, SMRs are able to produce both electricity and heat, allowing them to connect to many energy users. Industrial heat; thermal, chemical, or electrical energy storage; and dispatchable demands including thermal or electrical hydrogen generation, cryptocurrency mining, or district heating supplementation all allow SMRs to engage more profitability with fluctuating market conditions.

10. Longer Refueling Cycles

    Due to their size, SMRs have reduced fuel requirements, allowing them longer periods between each refueling. Some concepts feature online refueling where fuel is added as needed during operation. This reduces costs as the process of refueling can add significantly to overall costs.

11. Plant Efficiencies

As will be discussed in more detail later, some SMR concepts are expected to have increased efficiencies as compared to LRs. This reduces costs per MWe as fewer thermal megawatts (MWt, heat energy which can be converted to electricity) must be produced for each MWe.

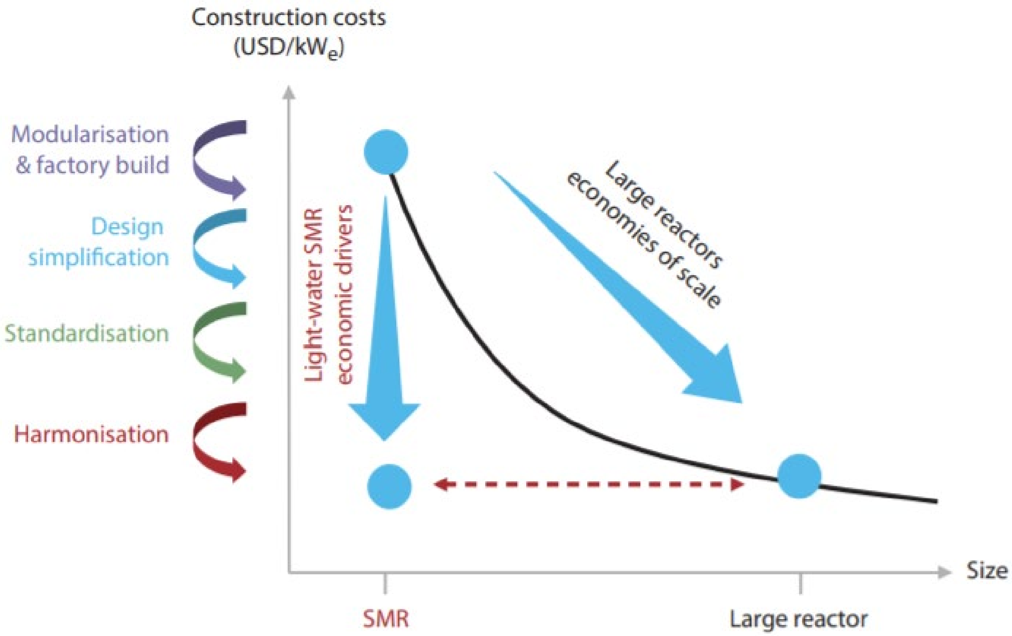


Figure 16. Cost factors of SMRs.

Figure 16 shows a (nontechnical) view of how the contrasting effects of diseconomies of scale and SMR manufacturing and design factors can lead to SMRs that are cost competitive against alternatives. The additional factors discussed above can further reduce costs of SMRs, but without manufacturing, construction, and operational experience, it is difficult to ascertain if the unique factors of SMRs will outweigh the diseconomies of scale. However, considerations that are not directly financial may also outweigh financial considerations, including the need for baseload generation, high reliability, and combined heat and power generation.

Appendix B
Literature on SMR Costs

(Vegel and Quinn 2017) – Bottom-Up Capital Cost Estimation for Generation IV Small Modular Reactors

Utilizing estimates of the construction costs and materials needed for nuclear- and non-nuclear components of SMRs, the authors construct a bottom-up cost estimation and contrast it with other capacities and generations of nuclear reactors. The paper discusses the cost effects of economies of scale and the relative strengths and weaknesses of LRs and SMRs. For example, the paper explores the differences in technological parameters including safety measures, factory fabrication, and co-siting economies. The bottom-up methodology provides a comparison point and a different perspective from the existing literature, which tends to more frequently utilize top-down estimation approaches. This article's methodology also allows for more granular comparison between specific concepts, differing by generation, coolant type, etc. Results of the paper show “lower costs associated with the Generation IV helium-cooled reactor than the Generation III+ pressurized water reactor”.

(Stewart and Shirvan 2022) – Capital cost estimation for advanced NPPs

Stewart and Shirvan 2022 constructs a bottom-up cost estimation for SMRs. This paper utilizes a high degree of granularity, utilizing “over 200 structures, systems, and components” to generate cost figures. Like other cost estimation papers, this article examines the contrasting effects of diseconomies of scale against the beneficial characteristics of SMRs, mainly economies of multiples, factory production and learning economies, shorter construction times, design simplification, and unit timing. (Stewart and Shirvan 2022) places a special emphasis on the factors of traditional-scale nuclear reactors that make them less competitive than SMRs, mainly their complexity that leads to time and cost overruns. By adding these parameters into the analysis, the authors provide a more comprehensive comparison between scales of reactors.

(SMR Start 2021) – The Economics of Small Modular Reactors

Utilizing cost estimates from other studies, (SMR Start 2021) examines the applicability and competitiveness of SMRs across U.S. markets, determining that SMRs could be important and cost competitive across a variety of applications. In addition, the paper highlights that nuclear meets several environmental qualities, (such as operational carbon neutrality), which will increase in importance as countries work to meet carbon reduction goals. The authors also work to examine both U.S. and global demand and how the factor relates to speed of deployment. Deployment further relates to learning economies and the FOAK costs reducing towards NOAK costs.

(Black and Peterson 2019) – Economic Impact Report: Construction and Operation of a Small Modular Reactor Electric Power Generation Facility at the INL Site, Butte County, Idaho

This paper conducts a regional EIA for the proposed NuScale SMR project at INL. The authors utilize a multi-county geography and multi-year construction and operation stages to capture the scope and duration of the effects on the region. To estimate these effects, Black and Peterson use proprietary cost estimates from NuScale to determine the amount of economic activity and spending within the region, and then employ IMPLAN to conduct Input-Output analysis to examine final impacts. This paper is relevant to SMR cost data because it provides a high-level overview of SMR costs based on a concept with a relatively high TRL.

(ScottMadden Management Consultants 2021) - Gone with the Steam

This article examines the effects of coal plant closures on regional economies and the potential for SMRs to mitigate these effects. Specifically, the authors investigate the quality (wages and stability) and quantity of jobs created and lost in addition to other economic and technological characteristics between the technologies.

(Mignacca and Locatelli 2020) - Economics and finance of Small Modular Reactors: A systematic review and research agenda

This article systematically reviews existing literature on SMR costs, highlighting important factors and areas for further research. The authors are careful to explain the differences between finance and economics regarding energy research, but also the necessity of combining the two for a comprehensive analysis. The analysis concludes that more research needs to be conducted on O&M and decommissioning costs, as well as the generation of a standardized methodology for future economic/financial analyses.

(Black, Aydogan et al. 2019) – Economic viability of light-water small modular nuclear reactors: General methodology and vendor data

(Black, Aydogan et al. 2019) utilizes NuScale LLC data to generate cost estimates for SMRs. However, this article does not discuss economic impacts on regions – instead estimating the cost of SMRs to allow future comparison against energy generation alternatives. The research utilizes a bottom-up code-of-accounts approach to estimate costs, for example increasing specificity from Account Number 20 (Capitalized Direct Costs), to 21 (Structures and Improvement), to 214 (Security Building). Bottom-up estimates can provide more accuracy than top-down estimates when requisite data are available. A comparison of costs between the NuScale concept and the Pressurized Water Reactor-12 reveals that NuScale’s SMR is expected to be less expensive per kilowatt capacity.

(Weimar, Zbib et al. 2021) – Techno-economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest

This report examines the applicability of SMRs to various markets. However, this paper focuses on a smaller geography, the Pacific Northwest. Additionally, the report examines applicability through a lens that combines both economic and environmental factors for a more comprehensive analysis. As states and countries shift towards carbon neutrality, additional financial burdens may be placed on carbon-emitting generation assets, increasing the competitiveness of low-carbon energy resources including nuclear and VREs. The paper concludes that transitioning away from carbon-emitting energy assets will require around 5 GWe of firm (stable generation, unlike VREs), carbon-neutral capacity. SMRs will need to compete with both enhanced geothermal systems and near-firm generation assets, but at NuScale’s NOAK cost, no subsidy would be required for economic competitiveness.

(IAEA Division of Nuclear Power 2020) – Advances in Small Modular Reactor Technology Developments A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 Edition

A comprehensive exploration of SMR technology, the above cited handbook provides a wealth of information to multiple areas of study. Chapters 10 and 22 are especially relevant to cost analysis and market applicability.

- (Boarin, Mancini et al. 2021) – Chapter 10
  This article provides a thorough discussion how disaggregated SMR costs are used to generate total cost values, with considerations including code-of-accounts estimations, costs of financing, risk factors, and economies of multiples. The width and breadth of this report makes it quite valuable for researchers attempting to estimate SMR costs.
- (Black, Shropshire et al. 2021) – Chapter 22
  Like other articles, the authors discuss the factors that make SMRs advantageous compared to NPPs and applicable to a wide array of energy and heat generation applications. Specifically, this report examines: "the market assessment and potential for SMR adoption in both developed and emerging economies". The chapter examines themes including climate change, energy access, the UN's Sustainable Development Goals, and opportunities and challenges for SMRs.

(Barenghi, Boarin et al. 2012) – Investment in different sized SMRs: economic evaluation of stochastic scenarios by INCAS code

This paper examines the relative competitiveness of SMRs against traditional-scale NPPs in terms of financial risk. SMRs may experience higher costs per megawatt capacity due to diseconomies of scale, but they can reduce risk by allowing for scalability (purchasing more or fewer units across a project management selected timeline).

Again, similarly to other papers discussed in this literature review, (Barenghi, Boarin et al. 2012) examines the factors like learning economies and modularity that make SMRs competitive against LRs. However, this paper differs in that it examines how these factors impact risk across a timeline and the following stochastic factors:

- Capacity factor
- O&M unit cost
- Fuel cycle unit cost
- D&D unit cost
- Delay on construction duration
- Annual extra cost in case of delay
- Annual inflation rate
- Risk-free rate
- Overnight construction cost
- Annual escalation rate for construction costs.

(Abdulla, Azevedo et al. 2013) – Expert assessments of the cost of light-water small modular reactors

In an effort to complement traditional "top-down" and "bottom-up" cost assessments, this paper utilizes expert assessments to estimate the costs of SMRs. The report finds that estimates vary over a large range – a factor of 2.5. For example, the OCC estimate for a 45MWe reactor is between $4,000 to $16,300 per kilowatt electric. Many of these estimates come from experts working with reactor design companies and although the estimates do not disclose proprietary data, they likely bring accurate data to the analysis.

(The Royal Academy of Engineering on behalf of Enigineering the Future 2010) – Nuclear Lessons Learned

One important determinant of overall SMR cost is "learning economies", the cost reduction that comes with experience and taking advantage of "lessons learned". This report collects these lessons learned, especially those relevant to the nuclear program in the United Kingdom. Information gathered is from both construction and operational stages of reactors.

(Locatelli, Mancini et al. 2012) – Using real options to evaluate the flexibility in the deployment of SMR

Like other articles reviewed in this section, this paper examines the contrasting effects of SMR's diseconomies of scale and competitive technological characteristics. The paper places a focus on researching both financial and technological parameters to determine "how much… the profitability of SMRs change with respect to LRs, if a ROA approach is used instead of a DCF approach".

(Locatelli and Mancini 2012) – A framework for the selection of the right NPP

As opposed to other papers presented in this section, this article presents a framework for plant selection instead of comparative cost estimations. This approach is taken to reduce the complexity and multidimensionality of plant selection. The proposed methodology involves two steps: first, the importance of factors is considered, and second, the TOPSIS scoring method is utilized to generate a simple final score. TOPSIS is "based on the assumption that the best alternative should have the shortest Euclidean distance from an ideal positive solution (made up of the best value for each attribute regardless of alternative) and the farthest distance from a negative ideal solution (made up of the worst values)"

(Locatelli and Mancini 2011) – Large and small baseload power plants: Drivers to define the optimal portfolios

This paper extends traditional analyses of plant portfolio optimization by including consideration of Mean Variance Portfolio theory, Internal Rate of Return, and – importantly – smaller nuclear plant sizes than are usually utilized for analysis. As compared to other papers, this analysis also researches more "niche" technical characteristics of SMRs, including Spinning Reserves Management, Technical Siting Constraints, and in-depth safety considerations. Using these factors, the report examines the following drivers: "plant size, Electricity Price, Carbon Tax and Market Dimension. By 'market dimension' we mean, from the point of view of a utility (or the investor), the total MWe to be deployed."

(Boarin and Ricotti 2009) – Cost and Profitability Analysis of Modular SMRs in Different Deployment Scenarios

Like other reports described here, this paper compares the financial competitiveness of SMRs against LRs based on the intrinsic financial characteristics of each. Specifically, the financial risk of "monolithic" construction of LRs is considered given the possibility of market downturns or demand shifts, as compared to the staggered construction of multiple SMRs with the opportunity to add more reactors or delay/cancel further construction given external factors. This focus parameter is layered with the traditional differences between the two types of reactors (i.e., modularity, factory construction, learning economies, etc.). The paper concludes that while SMRs experience an estimated 20% higher overnight capital cost (OCC), "SMRs may be considered as a valuable and flexible investment option, alternative to LRs, in a merchant plant environment, where capital-intensive projects are riskier due to significant sunk costs".

(Boarin and Ricotti 2011) – Multiple NPPs investment scenarios: Economy of multiples and Economy of Scale impact on different plant sizes

Like other papers in this literature review, this article examines the financial competitiveness impacts of characteristics held by SMRs and LRs. Unlike other papers, this analysis focuses specifically on the relationship between economies of multiples, (beneficial for SMRs), and economies of scale (beneficial for LRs). The paper concludes that economies of multiples are estimated to outweigh economies of scale for medium- and small-scale reactors, making these capacities of reactors competitive against LRs. However, the same does not hold true for very small reactors (VSRs), which require higher cost reductions from simplification and economies of multiples to outweigh diseconomies of scale. However, LRs are not appropriate for all use cases, meaning that some applications may utilize SMRs or VSRs even if LCOE costs are relatively higher than those of LRs.

(Carelli, Garrone et al. 2010) – Economic features of integral, modular, small-to-medium size reactors

This report discusses the comparative advantages and disadvantages of SMRs against LRs given technological and financial characteristics. However, this paper focuses on critiquing the application of economies of scale as a cost comparison variable between the two classes of NPPs. The article categorizes the factors that make SMRs unique, ("ad hoc factors"), and characteristics that are shared by the reactor classes, ("common factors"). The classification of these characteristics lends credibility to the argument that economies of scale is an inaccurate method to calculate SMR costs given their uniqueness from LRs.