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A Roadmap to Deploy Small Modular Reactors in Emerging Newcomer Countries to Sustainably Increase Energy Access – A Case Study of Tanzania

A Master's Thesis submitted for the degree of
“Master of Science”

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Affidavit

I, **JOANNE LIOU**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A ROADMAP TO DEPLOY SMALL MODULAR REACTORS IN EMERGING NEWCOMER COUNTRIES TO SUSTAINABLY INCREASE ENERGY ACCESS – A CASE STUDY OF TANZANIA", 91 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Efforts to achieve the target of universal access to energy services has made visible progress; however, gaps are still prevalent, mainly concentrated in remote and rural regions of developing states across Africa and Asia. As global efforts seek to implement clean and innovative solutions, the increased use of renewable energy coupled with the introduction of nuclear energy supplied by small modular reactors (SMRs) and micro modular reactors (MMRs) has the potential to fill such gaps.

For this thesis, 10 to 300 MW reactors are categorized as small, and less than 10 MW reactors are categorized as micro. This thesis examines considerations for SMR and MMR deployment and analyzes the International Atomic Energy Agency's Milestones Approach, in conjunction with SMR deployment indicators and the 3S concept – safeguards, safety and security. The analysis culminates in SMR and MMR deployment roadmaps that establish the timing for deployment between 4 to 10 years, compared with 10 to 15 years for a conventional nuclear power plant.

The benefits of deploying modular reactors to increase access to clean energy and to replace carbon-intensive sources of energy supply are discussed and demonstrated with a case study in Tanzania. Based on regional peak demand and Tanzania's generation and transmission plan by 2030, Tanzania has SMR deployment potential of about 4,750 MW, which would replace coal- and gas-powered plants and eliminate associated emissions. Furthermore, MMR deployment could play a significant role in helping Tanzania reach its 75 percent electrification goal by 2030. Tanzania's analysis provides a proxy for nuclear newcomers and interested countries that may face similar challenges concerning grid capacity and infrastructure in pursuit of introducing nuclear power into a country's energy portfolio.

Preface

The preliminary results of this master's thesis were published in conjunction with the International Atomic Energy Agency's Conference on Climate Change and the Role of Nuclear Power, 7-11 October 2019. Under the guidance of my thesis supervisor, Dr. Kaluba Chitumbo, and in collaboration with Naveesh Reddy, Senior Nuclear Consultant of RIENTEC, the conference paper included material related to the roadmap for deployment. Further research related to the Tanzania case study was completed for the poster presentation that I presented on 9 October 2019. The presentation was well-received by IAEA experts and nuclear industry counterparts. The audience feedback provided food for thought and motivation to pursue the topic further.

The study is representative of my overall interests in applying innovative technology toward sustainable development. As a former journalist in the oil and gas industry and communication specialist for an international social impact programme, I am keen to leverage my past experiences to align my career with my interests. The Environmental Technology and International Affairs programme at the Technical University of Vienna and the Diplomatic Academy provided that opportunity.

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List of Abbreviations

3S	Safeguards, Safety and Security
3SBD	Safeguards, Safety and Security by Design
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DOE	Department of Energy
EPZ	Emergency Planning Zone
FOAK	First of a Kind
GHG	Greenhouse Gas
Gt	Gigatonnes
GWe	Gigawatt Electrical Capacity
IAEA	International Atomic Energy Agency
ICONS	International Conference on Nuclear Security
IEA	International Energy Agency
LCOE	Levelized Cost of Electricty
MMR	Micro Modular Reactor
MW	Megawatt
MWe	Megawatt Electrical Capacity
MWt	Megawatt Thermal
NEI	Nuclear Energy Institute
NEPIO	Nuclear Energy Programme Implementing Organisation
NGO	Nongovernmental Organization
NOAK	Nth of a Kind
NOx	Nitrogen Oxide
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
PSMP	Power System Master Plan
PWR	Pressurized Water Reactor
S & T	Science and Technology
SDG	Sustainable Development Goal
SMR	Small Modular Reactor
SOx	Sulfur Oxide

SSAC	State Systems of Accounting for and Control of Nuclear Material
TAEC	Tanzania Atomic Energy Commission
TANESCO	Tanzania Electrical Supply Company
TNPP	Transportable Nuclear Power Plant
URT	United Republic of Tanzania
WANO	World Association of Nuclear Operators

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I would like to express my sincere gratitude for my adviser Dr. Kaluba Chitumbo, who provided exceptional guidance and encouragement in the pursuit of this thesis topic.

I appreciated all the positive thoughts, feedback and energy received from ETIA-12 classmates, IAEA colleagues, family and friends, near and far.

Thank you.

1. Introduction

The 2030 Agenda for Sustainable Development outlines 17 goals to transform the world and to promote prosperity while protecting the livelihood of Earth. Fundamentally, the 17 Sustainable Development Goals (SDGs) reflect some of the essential elements for survival and societal functions. One of these essential elements is energy. Energy plays a vital role in the 2030 Agenda and the Paris Agreement on climate change. Access to energy supports the realization of many SDGs, such as good health and well-being, clean water and sanitation, quality education, gender equality, industry and infrastructure, and economic growth. Moreover, the proliferation of access to energy that is intentionally clean, affordable and sustainable will reduce emissions and mitigate climate change.

Almost three-quarters of carbon dioxide (CO2), the primary human-caused greenhouse gas (GHG) emission, stemmed from the energy sector in 2016, according to the World Resources Institute (Ge and Friedrich 2020). Most emissions are generated from electricity and heat followed by transportation, manufacturing and construction, and fugitive emissions *(Figure 1-1)*. Most emissions are generated from electricity and heat, followed by transportation, manufacturing and construction, and fugitive

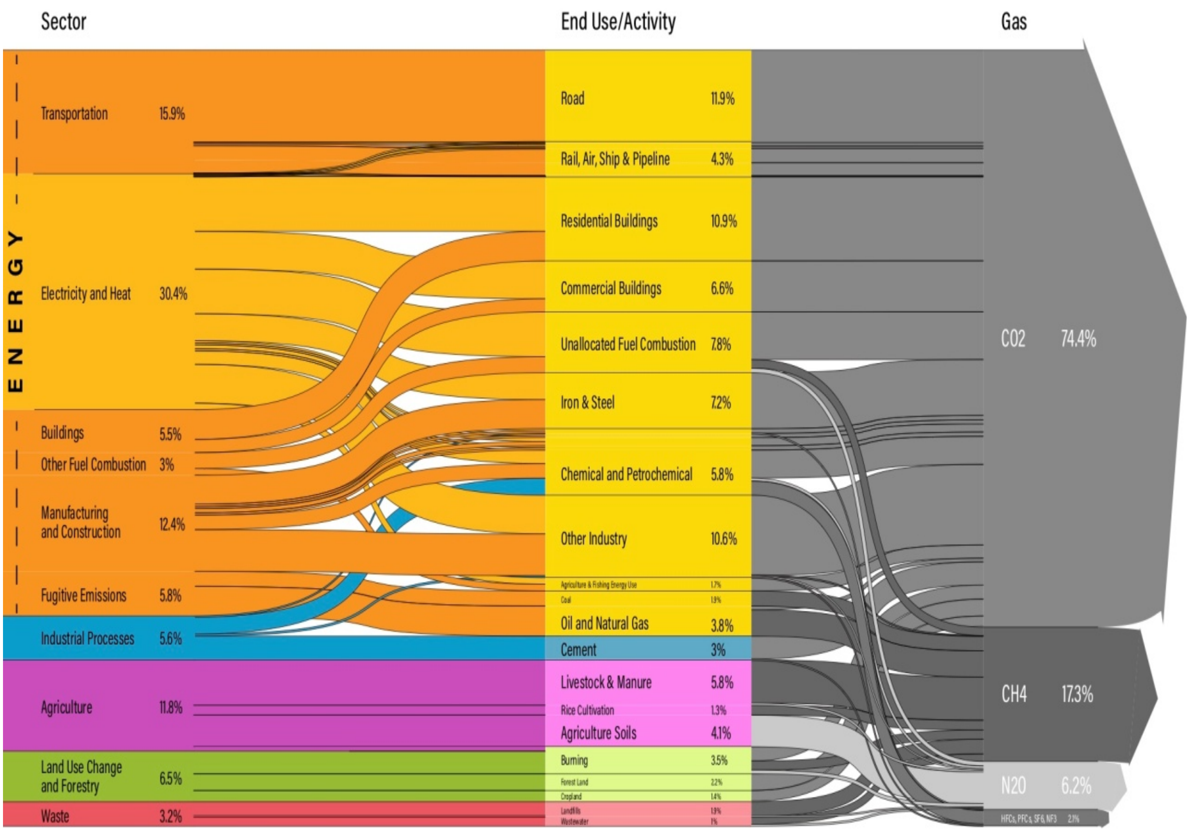


Figure 1-1: World Greenhouse Gas Emissions in 2016
(Ge and Friedrich 2020)

emissions (Figure 1-1). The path and transition toward energy sector decarbonisation to limit the global mean temperature increase must be inclusive of efficient, renewable, and low- or emission-free technologies. The International Energy Agency (IEA) recognizes the role nuclear power can play in the clean energy transition and electricity security. The IEA forecasts the energy demand met with fossil fuels *"will halve between 2014 and 2050, while the share of low-carbon sources, including renewables, nuclear and fossil fuel with carbon capture and storage, would more than triple worldwide to comprise 70 percent of energy demand in 2050"* (International Energy Agency and International Renewable Energy Agency 2017, 7).

Lowering carbon emissions and the effort to subscribe to emission-free, scalable energy sources are prevalent in pursuit of meeting energy demand and connecting areas without energy access. SDG 7 is to *"ensure access to affordable, reliable, sustainable and modern energy for all,"* and while nearly 9 out of 10 people have access to electricity, a significant gap persists between rural and urban areas (Department of Economic and Social Affairs 2019, 36). Remote and hard-to-reach communities represent the majority of the population without electricity, which equates to about 840 million people. *"In 2017, rural coverage was 78 percent compared to 97 percent in urban areas,"* according to The Sustainable Development Goals Report 2019, which means approximately 87 percent of people without electricity live in rural areas (Department of Economic and Social Affairs 2019, 36).

There are several options to increase energy production, and the potential for nuclear energy, specifically base-load, emission-free energy generated by small modular reactors (SMRs), is attractive because of its benefits related to environmental concerns and energy security. Many countries have identified nuclear power in their mix of possible energy sources, and SMRs have the potential to not only present a nuclear option but also replace high-emission oil, gas and coal sources. The increased use of renewable energy, such as solar and wind energy, coupled with SMRs, can fill gaps that are associated with increased access to energy and economic development, while simultaneously mitigating GHG emissions.

For this research, SMRs are further categorized as small – generating 11 to 300 MW – and reactors generating 10 MW or less are categorized as micro modular reactors (MMRs) to recognize inherent design differences (Table 1-1). Throughout the thesis, the reference to SMRs encompasses both sizes – small and micro. The two sizes will be differentiated to clarify statements, as necessary.

Table 1-1: Comparison of Nuclear Reactor Designs

Design Feature	Conventional Nuclear	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
Reactor Output (MWe)	1,000 – 1,700	11 - 300	1 - 10
Typical Output of Each Site (MWe)	2,000 – 3,400	100 - 600	1 - 100
Plant Footprint (Acres)	830	10 to 75	0.1 - 2
Fuel Cycle (Months)	12 - 24	24 - 48	120 - 360
Emergency Cooling System	Active	Passive	Passive
Reactor Cost (Billion USD)	5.0 - 10.0	0.06 - 2.0	0.02 - 0.15
Estimated Construction Time (Years)	5 - 6	< 3	< 2
Emergency Planning Zone	10-mile Radius from Reactor	Site Boundary	Site Boundary
Manpower for Operation	900 – 1,400	60 - 375	15 - 50

This thesis provides an introduction to SMR technology to demonstrate its potential and benefits for future utilization, particularly in emerging countries where lack of energy access is concentrated. Chapter 2 analyzes the conventional nuclear power plant roadmap by the International Atomic Energy Agency (IAEA) in conjunction with SMR deployment indicators, as defined by the IAEA. The analysis culminates in SMR and MMR deployment roadmaps. Chapter 3 evaluates the potential for SMR and MMR deployment in Tanzania to meet energy demand and replace high-carbon-emitting sources of energy. The case study proposes the geographical placement of SMRs and MMRs based on projected demand and grid capacity.

SMRs have yet to be commercially deployed, but as developments in bringing the technology to market continue to progress, the timeliness of this thesis provides a basis to consider and to prepare for the deployment of SMRs in the future.

1.1 Methodology

The research, conclusions and recommendations presented in this thesis are based on a multifaceted approach. Much of the background information is derived from literature reviews and information attributed to respected and recognized sources in or related to the nuclear energy industry. The case study on Tanzania is based on data found in the country's comprehensive Power System Master Plan 2016 Update. A questionnaire was later developed to further acquire additional and updated information from primary sources based in Tanzania to support the content and accuracy of the case study. However, due to the coronavirus pandemic, the research trip to Tanzania was cancelled.

The initial findings of this thesis were presented to an international audience at the IAEA's Conference on Climate Change and the Role of Nuclear Power, 7 - 11 October 2019, in Vienna, Austria, which allowed engagement with industry experts who provided constructive feedback and recommended additional sources. While attending the Combined Steering Committee and Working Groups Meeting of the SMR Regulators' Forum at the IAEA, 11 - 15 November 2019, as well as the International Conference on Nuclear Security at the IAEA, 10 - 14 February 2020, valuable insight and considerations from presenting experts contributed to the outcome of the content of this thesis.

Furthermore, given the prevalence of and interest in SMR technology, more recent presentations and webinars hosted by public and private institutions yielded relevant reference material.

1.2 Small Modular Reactors

In recent years, interest in SMR technology and potential for deployment as a clean and reliable source of energy has been growing. SMRs are defined by the IAEA as advanced reactors that are *"designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises"* (IAEA Department of Nuclear Energy 2018, 1). By definition, the reference to SMRs encompasses both small and micro categories. To put SMRs into perspective, reactors at large-scale, conventional power plants typically range from 600 MW to more than 1,000 MW. In the same vein as their larger counterpart, SMRs utilize nuclear fission to generate heat to produce energy, which can be used for electricity, hybrid energy systems, heating, water desalinisation and steam for industrial applications.

SMRs are not a novel technology, though they have yet to be widely deployed for commercial use. SMR technology has a 70-year history of operating worldwide in hundreds of moving vessels, such as submarines and aircraft carriers, which spend long periods in remote areas. Dating back to the 1950s, the United States military experimented with *"small reactors to power heavy overland cargo haulers and as* *substitute power in remote areas"* (Office of Nuclear Energy, Science and Technology 2001, 6).

Based on the IAEA Power Reactor Information System, there are also a handful of land-based small reactors in operation in China, India, Pakistan and Siberia (International Atomic Energy Agency 2020b). In the mid-1970s, remote from any grid, four 62 MWt (thermal) units began commercial operation at the Bilibino co-generation plant in Siberia, each producing 11 MW of electricity each and steam for district heating, operating *"much more cheaply than fossil fuel alternatives in the severe climate of this Arctic region"* (World Nuclear Association 2020b).

SMRs under development offer a range of outputs and opportunities for sustainable energy development, particularly in remote areas with less developed infrastructures. More than 50 commercial SMR designs are targeting different applications and varied outputs, including three SMRs in advanced stages of construction in Argentina and China (World Nuclear Association 2020b).

The limits of grid capacity and relevant infrastructures, which are challenges in emerging nuclear energy countries, will be addressed in consideration of the deployment of nuclear power to increase emission-free energy for a sizeable population. *"Micro reactors are 100 to 1,000 times smaller than conventional nuclear reactors,"* stated Alice Caponiti, Deputy Assistant Secretary for Fleet and Advanced Reactor Deployment at the U.S. Department of Energy (DOE). *"While one-megawatt electricity may not sound like a lot, that is enough to provide reliable, resilient and clean nuclear-generated electricity to a thousand homes in small and remote communities"* (American Nuclear Society 2020).

A number of countries, specifically in Africa, have identified or expressed interest in including nuclear power in their mix of energy sources. Grid capacity in most sub-Saharan African countries ranges from about 200 to 4,000 MW. *Table 1-2* lists the installed capacity of selected countries, including those interested in or already pursuing nuclear power. Therefore, the limited capacity is not suitable for large-scale nuclear power reactors. These countries are embarking on rural electrification programmes using a mix of energy sources (hydro, thermal and renewables). Considering infrastructure limitations and costs, SMRs that provide a smaller range of energy at a fraction of conventional nuclear power programmes have the potential to play an impactful role in countries that aspire to or plan to introduce nuclear power into their energy portfolios.

Table 1-2: Power Generation Capacity

Country	Installed Capacity (MW)	Main Source(s) of Power	Access Rate (% of population)	Access Rate of Rural Population
Burkina Faso	300	Diesel and Heavy Fuel Oil	20.3	1.5
Egypt*	38,860	Thermal and Hydropower	100	100
Ethiopia*	4,206	Hydroelectric	40	29
Ghana*	4,399	Thermal	83	50
Kenya*	2,351	Hydroelectric	64.5	57.3
Liberia	126	Hydropower	12	3
Malawi	439	Hydroelectric	10.8	1
Niger	284	Fossil Fuels	11.2	0.4
Rwanda*	218	Thermal and Hydroelectric	30	12
Senegal*	864	Thermal	64	43.5
Tanzania*	1,504	Thermal	32.7	16.8
Togo	230	Thermal	35	5
Uganda*	947	Hydro	19	19
Zambia*	2,800	Hydroelectric	31	4

**Considering, planning or starting nuclear power programmes*

Sources: Power Africa 2018, World Bank Open Data 2020 and World Nuclear Association 2020a

1.2.1 Global Developments toward Commercialization and Deployment

Both public and private institutions are actively participating in efforts to bring SMR technology to fruition *(Table 1-3)*. More than 50 different SMR designs are being marketed, but only a handful are under construction. Established household names, such as Rolls-Royce and GE, as well as start-up companies, universities, government entities and multinational consortiums, have invested millions of dollars and human resources toward research and development.

The ongoing developments and deployment projections foreshadow SMRs having a tangible impact in the next decades on the energy industry and global efforts to meet energy demands while lowering emissions *(Figure 1-2)*. Based on data from the Nuclear Energy Agency and the IAEA, in a high-case scenario, *"up to 21 GWe of SMRs could be deployed in 2035, representing about 3 percent of the total installed nuclear capacity in the world. Thus about 9 percent of the total nuclear new build in 2020 to 2035 could be SMRs"* (Lokhov and Sozoniuk, Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment 2016, 10).

Table 1-3: SMR Development Around the World

Name	Organization and Country	Output	Type	Coolant	Moderator	Status
CAREM-25	National Atomic Energy Commission of Argentina	27 MWe, 87 MWt	Integral PWR	Light Water	Light Water	Under Construction
Integral Molten Salt Reactor-400 (IMSR-400)	Terrestrial Energy, Canada	194 MWe, 400 MWt	Molten Salt Reactor	Fluoride Salts	Graphite	Under Design
ACP100	China National Nuclear Corporation and China Guodian Corp.	125 MWe, 385 MWt	Integral PWR	Light Water	Light Water	Under Construction
Super-Safe, Small and Simple Reactor (4S)	Toshiba and Central Research Institute of Electric Power Industry, Japan	10 MWe, 30 MWt	Fast Neutron Sodium Reactor	Sodium	No Moderator	Under Design
System-Integrated Modular Advanced Reactor (SMART)	KAERI, Korea	100 MWe, 330 MWt	Integral PWR	Light Water	Water	Licensed
eVinci	Westinghouse, USA	25 MWe	High Temperature, Heat Pipe Reactor	Heat Pipe	Metal Hydride	Under Design
NuScale Power Modular and Scalable Reactor	NuScale Power, USA	45 MWe, 160 MWt	Integral PWR	Light Water	Light Water	In Design Certification Process
BWRX-300	Exelon, Oak Ridge National Laboratory, University of Tennessee-Knoxville and GE Hitachi, USA	300 MWe	Boiling Water Reactor	Light Water	Light Water	In Licensing Process
Aurora	Oklo, USA	1.5 MWe, 4 MWt	Fast Neutron Reactor	Heat Pipe		In Licensing Process
KLT-40S	Afrikantov OKB Mechnical Engineering, Russia	70 MWe, 300 MWt	PWR	Light Water	Light Water	Under Construction
Stable Salt Reactor	Moltex Energy, UK	37.5 MWe, 94 MWt	Molten Salt Reactor	Fluoride Salts	Graphite	Conceptual Design

Sources: International Atomic Energy Agency 2013, IAEA Department of Nuclear Energy 2018, General Electric 2020

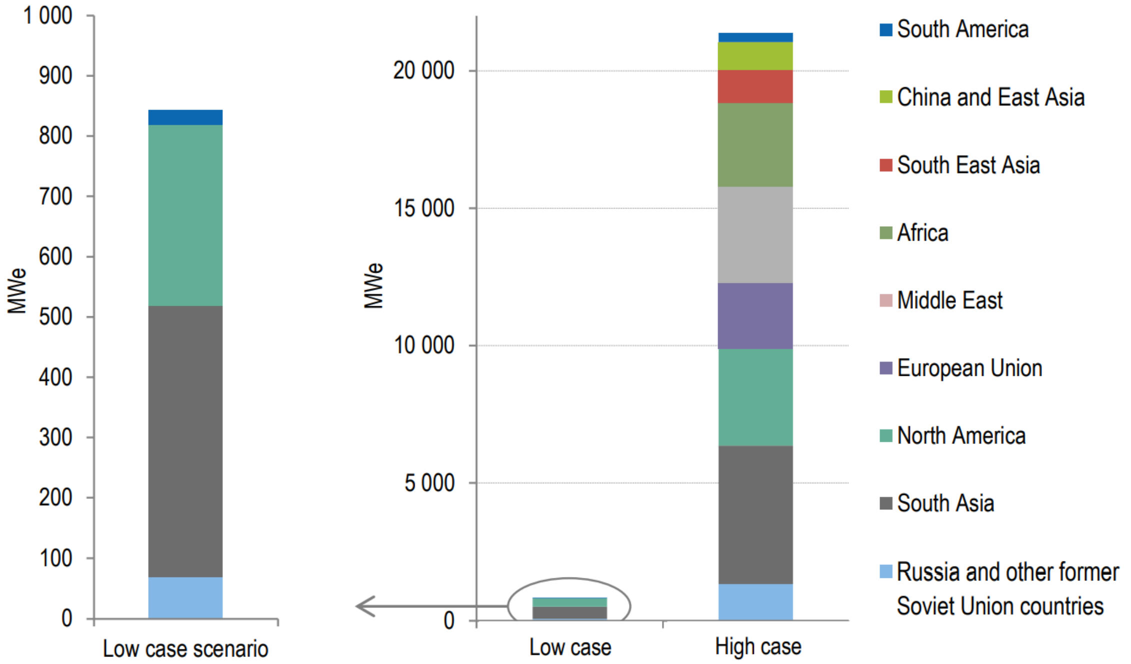


Figure 1-2: Estimated SMR capacity in 2035 by region
(Lokhov and Sozoniuk, Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment 2016, 11)

NuScale, an Oregon-based startup that partners with university researchers, plans to deploy its SMR on the Idaho National Laboratory site in mid-2020. NuScale is expected to receive the first SMR design certification from the U.S. Nuclear Regulatory Commission (NRC) in 2020. It has already received more than USD 280 million in investments from the U.S DOE (NuScale Power 2020a). Additionally, in March 2020, California-based Oklo submitted the first advanced reactor license application to the NRC for its Aurora 1.5-MW microreactor (Chan 2020), which is expected to begin demonstrations at the Idaho National Laboratory by 2025.

In May 2020, the U.S. DOE awarded research grants to projects that utilize GE Hitachi's BWRX-300, a 300 MWe water-cooled, natural circulation SMR. A project led by GE Research, in collaboration with Exelon Generation, Oak Ridge National Laboratory, University of Tennessee-Knoxville and GE Hitachi Nuclear Energy, will develop a digital replica of the SMR components and utilize artificial intelligence to make risk-informed decisions, ultimately to reduce the cost of operation and maintenance (General Electric 2020). In January and February 2020, GE Hitachi began the regulatory licensing process for its SMR in the U.S. and Canada, respectively. Countries like Poland, the Czech Republic and Estonia have expressed interest in introducing the BWRX-300 as a future energy source.

Separately, in May 2020, the U.S. DOE also launched a USD 230-million advanced reactor programme to accelerate the demonstration of advanced reactors *(Figure 1-3)*, including SMRs and MMRs (U.S. Office of Nuclear Energy 2020b). In the first of three categories of the programme, funding will go toward reactor designs that are expected to be in operation within seven years of the award.

Figure 1-3: Advanced Reactor Features
(U.S. Office of Nuclear Energy 2020a)

In the U.K., through the government's Nuclear Innovation Programme, a SMR consortium led by Rolls-Royce received an initial investment of GBP 18 million in 2019. The engineering firm plans to commission its first SMRs in 2029, as part of the U.K.'s aim to achieve net-zero emissions by 2050 (World Nuclear News 2020).

China's first SMR is estimated to begin operation in May 2025 (Global Construction Review 2019). The multi-purpose, 125-MWe ACP100 SMR is a joint venture between China National Nuclear Corporation and China Guodian Corp. In 2016, the ACP100 became the first SMR to pass a safety review by the IAEA.

In parallel to the technical development of SMRs, countries, such as Estonia, Poland and Romania, have launched pilot programmes and studies to prepare for potential deployment. In October 2019, Fermi Energia of Estonia agreed to collaborate with GE Hitachi on the potential deployment of the BWRX-300 SMR, and in January 2020, the startup began an evaluation of site proposals (Dalton 2020). *"If we do not deal with this discussion and research today, then in 10 years it could be too late, and the opportunity will be gone,"* said Kalev Kallemets, Fermi Energia's founder and chief executive officer, in an article published by NucNet. Estonia is energy-independent but also has the second-highest CO_2 intensity of all IEA countries after Australia, given its sizeable domestic oil shale reserves. Kallemets explained that the Baltic country *"needs* *to consider new generation SMR technology to maintain energy independence and achieve climate neutrality"* (Dalton 2020).

1.3 Advantages of Small Modular Reactors

Many benefits of SMRs are inherently linked to the nature of its design – small and modular – and could be argued for both niche and traditional markets. The main differences between SMRs and larger nuclear power reactors are the SMRs' lower power output and modular design. Structures, systems and components comprise the stand-alone SMR, which can be transported to the construction site for installation. The integrated design allows for passive safety and heat removal systems, reduced fuel requirements and, for some, underground containment. The advantages, as well as the challenges that follow, offer a sampling of various points that have been made in the general conversation surrounding SMRs and their potential for deployment.

1.3.1 Small and Modular

While there are dozens of designs being proposed and under development for SMRs, the common denominator among them all is their small size and modularity in construction. Fewer materials and resources related to the construction and operation of a SMR are necessary. In terms of human resources, the SMR could require as little as 15 people to operate, while larger power plants require between 900 to 1,400 people (Chitumbo 2019). At about one-third to one-fourth the size of a traditional nuclear power plant *(Figure 1-4)*, major components of SMRs, such as the reactor vessel, steam supply and cooling system, are expected to be small enough to be factory produced. The reactor vessel itself will be compact enough to be transported by boat, truck or railway. NuScale's SMR measures 65 ft (19.8 m) tall and 9 ft (2.75 m) in diameter, and its containment vessel measures 76 ft (23.2 m) by 15 ft (4.6 m) in diameter (NuScale Power 2020b).

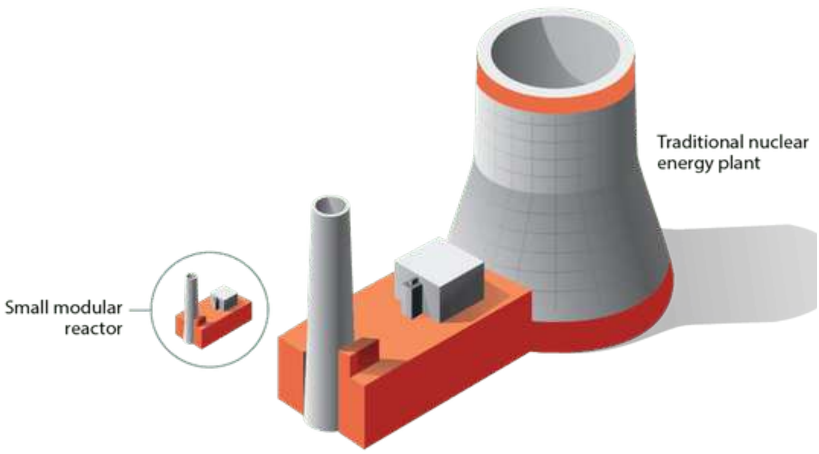


Figure 1-4: Size Comparison of SMR and Traditional Nuclear Plant (Idaho National Laboratory 2020)

Modularity enables efficient and consistent production, as well as decommissioning, in a controlled factory environment as opposed to the variability of an outdoor construction site. Countries, particularly newcomers and emerging nuclear countries, can incrementally build nuclear resources as it introduces nuclear power. SMRs enable the standardization of components and design, creating economies of mass production, rather than economies of scale often sought in large nuclear power plants. *"While typical large reactor projects can take up to 10 years or more to build, SMRs should be able to be built in far less time, perhaps in as little as three years"* (Zabielski 2018). Theoretically, a multi-unit SMR facility could be constructed on a staggered schedule, which would lower the risk of cost and schedule overruns for each unit, allowing for phased financing.

The compact nature of SMRs makes them suitable for remote locations, where SMRs do not require a large power grid and can be attached to other modules to increase emission-free power supply. This is especially relevant for countries with smaller electrical grids, where SMRs would be compatible with existing power grids or where SMRs would be able to provide an off-grid alternative. Remote and rural areas often rely on diesel generators, although the cost of fuel and the transportation of fuel can be costly. *"In remote communities, such as Alaska, where the fuel to run generators is costly to deliver, electricity prices can be up to 16 times higher than the national average and can consume up to half the income for a household,"* Caponiti explained (American Nuclear Society 2020).

1.3.2 Low Emission, Reliable Energy Production

As countries shift to and consider expanding clean energy sources, a range of technologies, including nuclear energy, will be needed. The application of SMRs could help achieve this movement and help reduce human-made carbon emissions. With nuclear power, about 55 Gt of CO_2 emissions in the past 50 years was avoided, equivalent to two years of global energy-related CO_2 emissions (International Energy Agency 2019). Coupled with intermittent power sources, such as wind and solar, SMRs can provide a constant and reliable source of baseload power. *"Nuclear energy technologies have reliably and economically produced about 20 percent of the electrical generation in the United States over the last two decades, and nuclear energy remains the single largest contributor of non-greenhouse gas emitting electricity generation in the U.S. (...) about 60 percent,"* said Shane Johnson, Deputy Assistant

Secretary for Reactor Fleet and Advanced Reactor Deployment in the Office of Nuclear Energy at the U.S. DOE (NICE Future 2019).

The emissions produced by the nuclear fuel cycle can be examined for a more holistic perspective of emissions associated with nuclear power. In a life cycle assessment study by the University of Saskatchewan, the GHG emissions produced from uranium mining and milling operations – one of the first stages of the nuclear fuel cycle – contributed about one gram of CO_2e/kWh to the nuclear fuel cycle, which equates to approximately less than 10 percent of the 12 grams of CO_2e/kWh produced by nuclear power (Parker, McNaughton and Sparks 2016). Accordingly, the UN Intergovernmental Panel on Climate Change reports that lifecycle GHG emissions from electricity supplied by coal produce over 800 grams/kWh, and natural gas produces about 500 grams/kWh (Bruckner, Bashmakov and Mulugetta 2014, 539).

1.3.3 Affordability and Stability

Considering the nuclear options, the overall cost of a SMR is projected to be more affordable for most emerging nuclear newcomer countries than large nuclear power plants, which may cost between 5 to 10 billion USD. The absolute cost of one SMR unit could be below 1 billion USD (Lokhov and Cameron, OECD/NEA Study on the Economics and Market of Small Reactors 2013, 702). *"The idea behind the SMR is to build several smaller reactors that are easier to finance as each module costs a few hundred million dollars each rather than several billions"* (Aris 2019).

Furthermore, the existing nuclear fleet and ongoing newbuild projects are challenged with cost overruns and delays. Given the versatility of SMR applications, SMRs could be used to offset the high cost of the production of hydrogen or desalination of water. NuScale argues, *"using excess energy for desalination may be a lucrative market, helping offset desalination's comparatively high electricity costs"* (Parshley 2020).

For the end-user, nuclear power offers not only a stable supply of power but also price stability. The cost of fuel comprises about 10 percent of the cost of producing nuclear power, while the cost of fuel comprises about 70 percent of the cost of producing power from gas (Aris 2019). While commodity prices fluctuate, the cost of power generated from SMRs is primarily fixed and not subject to market conditions.

1.4 Challenges of Small Modular Reactors

Claims touted as benefits of SMRs could also be used to argue against it. Both sides of the conversation are well supported by public and private institutions, highlighting keen interest, as well as high uncertainty and pushback. Given the novelty of the modular reactors, some challenges might not be known until the demonstration of the technology. For companies to invest, and the public to buy in, confidence in the new technology is critical.

1.4.1 Cost

While the forecasted economics of SMRs are conceptually attractive, the drivers for the economics of SMRs are theoretical and are yet to be demonstrated in practice. For cost savings and benefits of the modularity of SMRs to be realized, large quantities would need to be mass-produced. The cost dilemma is a catch-22; developers need orders to make investments in factory production, while customers need assurance in the technology's cost and realization. Adding to the challenge, there are dozens of SMR designs – some based on tried-and-true operations and others based on new technologies – making it harder to envision efficient production and mass manufacturing of a standardized SMR. The UK National Nuclear Laboratory estimates that at least 5 GW of total installed capacity of a repetitive standardized design would have to be produced for SMRs to be economical for a vendor (Aris 2019).

Economic and financial issues present the main challenges in the initial development of the technology, and the upfront and initial costs of new technologies often hinder adoption. The International Energy Agency recommends governments to fund SMR projects and introduce policies to ensure nuclear power plants of smaller scale are built safely (International Energy Agency 2019).

Moreover, the economics of SMRs is arguable, considering the economies of scale concept, cheaper sources of power, such as natural gas, and a lack of policy incentives to cut GHG emissions. While estimates will vary per design, location and market conditions, a joint study between Texas A&M University and the Czech Technical University found that *"the predicted fuel cost is 15 to 70 percent higher for integral pressurized water reactor type small and modular reactors than for currently operating or under-construction large reactors"* (Pannier and Skoda 2014).

1.4.2 Licensing

The nuclear industry has very specific licensing needs because of distinct concerns and public interest. Licensing is a process that varies from country to country, and it demonstrates compliance with requirements, mainly related to safety and security, in terms of design, site selection, construction and operation. Advanced designs, many of which have never been licensed before, are expected to challenge resources and technical expertise. While the licensing process in most countries has been developed for large nuclear power plants built one at a time, current licensing regimes do not support the cost-efficient deployment of SMRs. Licensing SMRs with novel features, such as different moderators or passive cooling, is a challenge and usually associated with more time, costs and uncertainties related to the outcome of the licensing process. *"Short construction schedules will not be fully benefitted from if the long licensing process prolongs the commissioning and approach to full-power operation"* (Soderholm 2013).

For emerging nuclear countries, the lack of an international standard for the licensing process could be a major hurdle to deployment. *"International standardization of licensing, as well as harmonization of regulatory requirements, has been a goal of several programmes (...) Based on their size and design characteristics, SMRs can be seen as an early opportunity for seeking multi-lateral or international regulatory approvals,"* according to a report published by the World Nuclear Association (Cooperation in Reactor Design Evaluation and Licensing Working Group 2015). Most SMRs have technical features that set them apart from currently deployed commercial reactors. The IEA recommends that policies are established to ensure *"licensing processes do not lead to project delays and cost increases that are not justified by safety requirements,"* as well as to support standardization across the nuclear industry (International Energy Agency 2019).

1.4.3 Public Perception

Already an issue for the nuclear industry at large is the public's perception surrounding nuclear power and spent fuel management. The unfamiliarity and uncertainties of a "new" technology exacerbate this challenge for SMRs. While governments may express interest and intention to introduce nuclear power as part of their energy portfolios to meet demand and in an effort to curb emissions, stakeholders must be involved and in agreement. Stakeholders include the general public, media, NGOs, local leaders or representatives, etc. *"Continuous, open, transparent and fact-based communication and dialogue with the society at large, as well as among all key organizations in nuclear power, contributes to safety, security and overall feasibility of nuclear power programmes,"* according to the IAEA (Dyck and Berthelot 2019).

The adage – knowledge is power – is appropriately applicable to this challenge. It is of utmost importance to keep the public well informed, engaged and acknowledged. A 2010 report by the Nuclear Energy Agency found that *"large parts of the public are still unaware of (or choose not to believe) the potential benefit of nuclear energy to reduce the emissions of climate change related carbon dioxide"* (Kovacs, Eng and Gordelier 2010, 7). Though opinions shift in time and vary among demographics, the consensus correlating knowledge to support is not limited to the nuclear energy industry but to most public topics up for debate. In regards to nuclear energy, public support is reduced because of concerns with *"terrorism, radioactive waste disposal and the misuse of nuclear materials, in that order"* (Kovacs, Eng and Gordelier 2010, 7).

At the IAEA's Technical Meeting on Stakeholder Involvement and Communication for New and Expanding Nuclear Power Programmes in Vienna, 11 to 14 June, the benefits of periodic research through surveys, focus groups and other mechanisms were highlighted. *"It is surprising how often there is a disconnect between the very knowledgeable, passionate nuclear scientist and the general public or other stakeholders whom we are trying to reach with our messages,"* said Sandy Wilkes from Bisconti Research (Dyck and Berthelot 2019).

To manage public perception in its partnerships with emerging nuclear countries, such as Laos, Paraguay, Rwanda and Zambia, Russia's state nuclear corporation, Rosatom, has committed to specific agreements targeting public outreach and education. In October 2016, Rosatom signed an agreement with Paraguay, which included developing programmes to increase public awareness about nuclear technologies and their applications, and in July 2019, Rosatom and Laos' Ministry of Energy agreed to cooperate on education, training and shaping public opinion efforts toward nuclear energy (World Nuclear Association 2020a). Rosatom has been growing its presence in Africa. Among its various activities, with Zambia, Rosatom and the Ministry of Information and Broadcasting Services are *"developing educational materials in both English and local languages to promote nuclear energy"* (World Nuclear Association 2020a). In February 2019, Rosatom and the Ministry of Infrastructure of Rwanda signed a memorandum to inform the public about nuclear technologies, which included engaging journalists, experts, teachers and students (Rwanda Ministry of Infrastructure 2019).

1.5 Spent Fuel Management

One of the longstanding topics surrounding nuclear energy is spent fuel management. The realm of SMR designs varies by physical size, fuel type and enrichment level, refuelling frequency and site requirements; therefore, spent fuel management practices are largely dependent on the type of SMR. *"Solutions for managing spent fuel and radioactive waste arising from SMRs will be one of the most important factors to take into account when choosing a technology, along with the security of fuel supply,"* according to Christophe Xerri, Director of the Division of Nuclear Fuel Cycle and Waste Technology at the IAEA (Chatzis 2019).

In the interest of emerging nuclear newcomer countries, SMR designs that require less frequent refuelling should be taken into consideration *(Table 1-4)*. SMR designs have reactor cores made for potentially long-term, unattended operations, and they target countries with small electric grids or remote locations. *"These reactors tend to be liquid, metal-cooled fast reactors with fresh fuel, having high uranium enrichment levels"* (Ramana and Mian 2017). In consideration of the latest technical developments toward Generation IV reactors, a closed nuclear fuel cycle may be realized. Within these designs, existing nuclear waste will be utilized in the production of electricity.

Table 1-4: Estimated Fuel Cycles of Different SMRs

SMR Type	Technical characteristics	Fuel Cycle Length
Integral PWR	Smaller size, lower fuel burnup	12 - 48 months
Molten Salt Reactor	Molten fuel, continuous processing	Continuous Operation
Fast Reactors	Higher power density and higher fissile content, molten metal coolants	6 - 24 months
Nuclear Batteries	Higher fissile loading, small size, possibly unmonitored operations	30 years (360 months)

Sources: Ramana and Mian 2017, International Atomic Energy Agency 2013

As a function of being fabricated and fuelled in a factory, SMRs are intended to be returned to the factory for defueling at the end of its lifecycle, which could be up to a few decades. Refuelling for conventional nuclear power plants takes place every one to two years. The IAEA remarks that some SMRs are *"designed to operate for up to 30 years without refuelling. Nevertheless, even in such cases, there will be some spent fuel* *left, which will have to be properly managed"* (Chatzis 2019). It will be critical for emerging nuclear newcomers to consider how to handle spent fuel in the long run and ensure that a contractual arrangement or agreement is in place with the vendor.

1.6 Emerging Nuclear Energy Countries

In addition to 30 countries with operational nuclear reactors, *"about 30 countries are considering, planning or starting nuclear power programmes, and a further 20 or so countries have at some point expressed an interest"* (World Nuclear Association 2020a). These countries range from sophisticated economies to emerging and developing countries.

The limits of grid capacity and relevant infrastructures are challenges in nuclear newcomer countries, further supporting the argument for SMRs over large-scale power plants. According to the IAEA Milestones Approach, a single power plant should represent no more than 10 percent of the total installed capacity (International Atomic Energy Agency 2015, 36). The practical limit of the generating unit size that can be installed restricts deployment of conventional nuclear power and supports SMRs for near-term deployment.

As demonstrated in *Table 1-2*, installed grid capacity in African countries could be a limiting factor and challenge to energy expansion. These countries are embarking on programmes of rural electrification using a mix of energy sources (hydro, thermal and renewables). From the perspective of a country that is new to nuclear power, SMRs are more feasible than large-scale nuclear power plants and could take the place of or be utilized in addition to other sources of energy. Nuclear energy provides a reliable complement to renewable sources that are dependent on climate conditions. In consideration of limitations, costs and implementation, SMRs that provide a smaller range of energy have the potential to play an impactful role for these countries that aspire or plan to introduce nuclear power into their energy portfolios.

About 14 percent of the world's population resides in sub-Saharan Africa; however, as seen in *Figure 1-5,* nearly half of that population is without access to electricity (Blimpo and Cosgrove-Davies 2019). The lack of electricity to support residents, as well as industries, limits countries' overall growth, socially and economically. The role of nuclear power is not only a matter of access but also of industrialization and development. SMRs can target specific industries, which could have far-reaching implications for the country's economic development. As discussed earlier, apart from electricity generation, SMRs could be used for other applications, such as water desalination, hydrogen production, industrial/process heating and district heating.

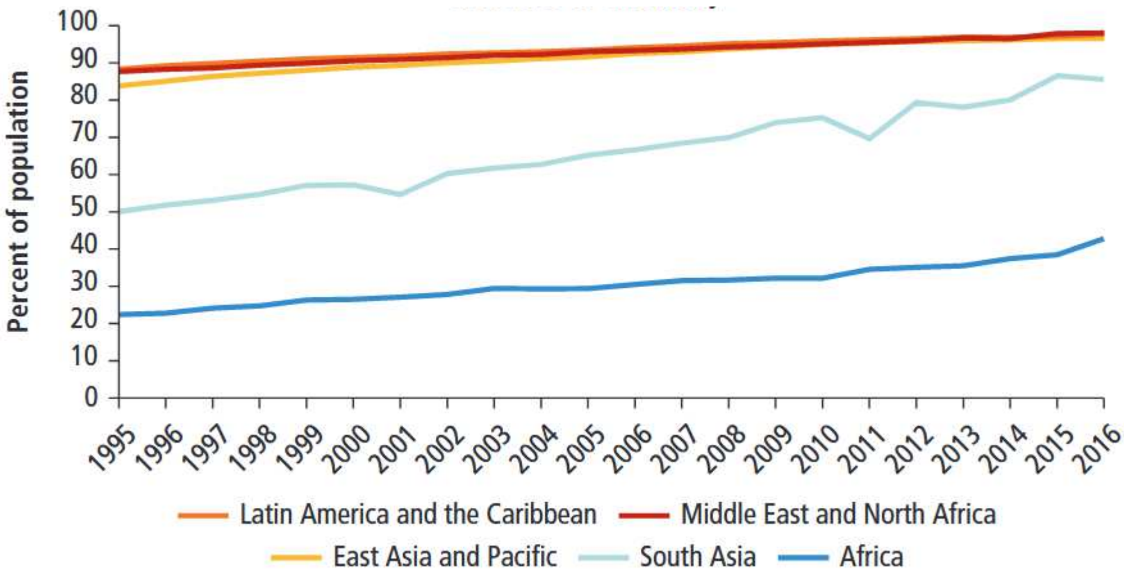


Figure 1-5: Access to Electricity
(Blimpo and Cosgrove-Davies 2019)

2. Developing a Roadmap for Deployment

The concept of leapfrogging applies to many emerging nuclear newcomer countries. The adoption of renewable energy is an example of bypassing the encompassing creation of an energy infrastructure centered on high-polluting fossil fuels. The potential adoption and deployment of SMRs could further the "leap" to achieve sustainable, affordable and clean energy supply.

As the development of SMR technology progresses, deployment is imminent, and guidance for nuclear newcomers is imperative. Points of consideration are similar between large-scale nuclear power plants and SMRs; therefore, the IAEA Milestones Approach, which aims to assist countries in introducing a large-scale nuclear power programme, provides a foundation for developing the succeeding roadmaps for SMRs and MMRs. However, the smaller size, range of outputs and technological differences of SMRs and MMRs produce some discrepancy in, as well as a more significant opportunity for deployment.

An analysis of the IAEA's SMR deployment indicators, as well as input from experts, international legal guidance and the 3S concept – safeguards, safety and security – will subsequently inform and shape the adaptation of the IAEA's Milestones Approach. From the perspective of SMRs and MMRs, the 19 nuclear infrastructure issues are evaluated for each of the three milestones to reflect the extent and differences in which the issue is relevant for the modular reactors. Annex 1 presents the line-by-line conclusions for both SMRs and MMRs. The results of the analysis culminate in adapted deployment roadmaps for SMRs and MMRs.

2.1 Milestones Approach

Three phases comprise the IAEA Milestones Approach, a comprehensive roadmap for countries planning for their first nuclear power plant. There are 19 nuclear infrastructure issues *(Table 2-1)* that are considered throughout each of the three phases, which is earmarked by reaching the corresponding milestone (International Atomic Energy Agency 2015). The roadmap to deployment, which is estimated to take at least 10 to 15 years, guides decision-makers and experts on the central issues and activities to be addressed for a holistic approach to introduce nuclear power to provide for safe, secure and sustainable energy.

Table 2-1: The 19 Infrastructure Issues

1. National position	11. Stakeholder involvement
2. Nuclear safety	12. Site and supporting facilities
3. Management	13. Environmental protection
4. Funding and financing	14. Emergency planning
5. Legal framework	15. Nuclear security
6. Safeguards	16. Nuclear fuel cycle
7. Regulatory framework	17. Radioactive waste management
8. Radiation protection	18. Industrial involvement
9. Electrical grid	19. Procurement
10. Human resource development	

Source: International Atomic Energy Agency 2015, 7

The IAEA's Milestones Approach will be analyzed in terms of SMR and MMR deployment *(Figure 2-1)*. The IAEA suggests that governments establish a mechanism tasked with coordinating the various organizations involved in the development of the energy programme, such as major utilities, the regulatory body for security and radiation safety, public stakeholders, legislative representatives and other decision-makers. Within the roadmap, legislation is considered early in the development effort.

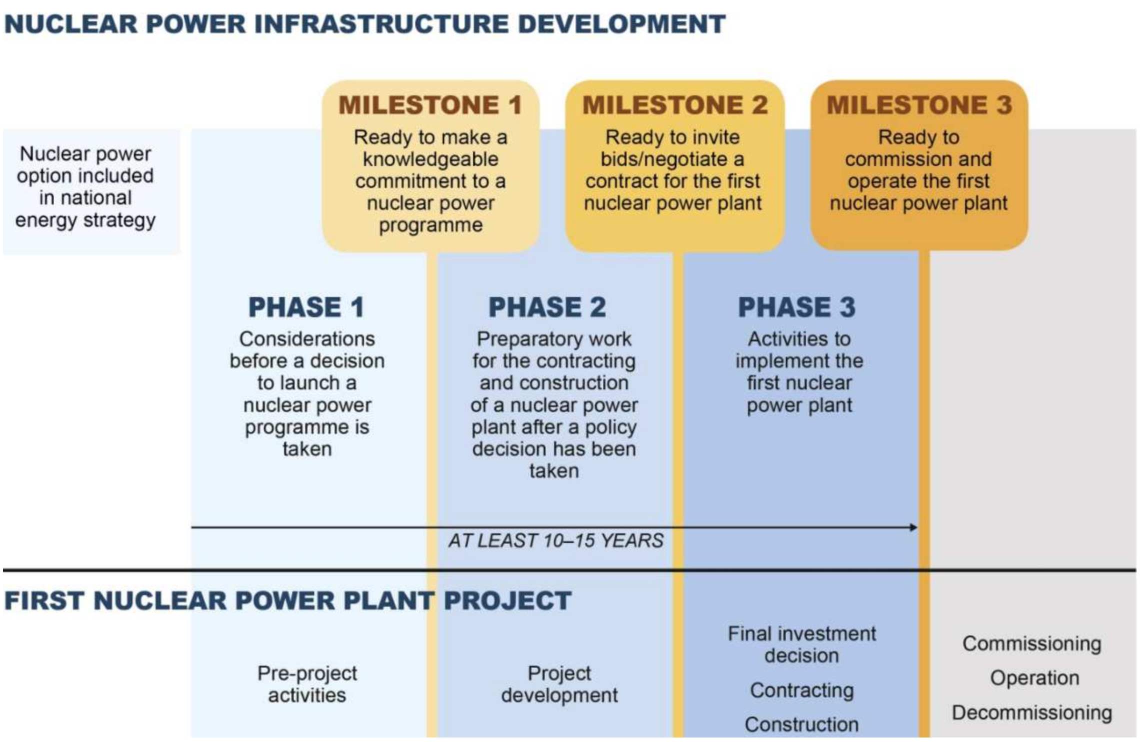


Figure 2-1: IAEA Milestones Approach
(International Atomic Energy Agency 2015, 5)

To demonstrate the process of the approach, the following discussion follows the legal framework through the three phases, which culminate in three milestones.

Regardless of the technology and size – conventional reactor, SMR or MMR – the international legal framework apply to countries pursuing nuclear energy.

2.1.1 Milestone 1

The first phase focuses on the requirements for a legal framework and establishing an independent nuclear regulatory body and system of authorization, inspection and enforcement. In the IAEA's *Milestones in the Development of a National Infrastructure for Nuclear Power*, the Agency suggests that a nuclear power programme's regulatory framework include:

- *Designation of an effectively independent competent regulatory body with clear authority, adequate human and financial resources and strong government support;*
- *Assignment of core safety, security and safeguards regulatory functions for developing regulations, review and assessment, authorization, inspection, enforcement and public information;*
- *Authority and resources to obtain technical support as needed;*
- *A clear definition of the relationship of the regulatory body to other organizations;*
- *Clearly defined responsibilities of licensees;*
- *Authority to implement international obligations, including IAEA safeguards;*
- *Authority to engage in international cooperation;*
- *Provisions to protect proprietary, confidential and sensitive information;*
- *Provisions for stakeholder involvement and communication with the public* (International Atomic Energy Agency 2015, 32).

The framework establishes an independent regulatory body and scopes of authority. Upon completion of Phase 1, the member state is ready to commit to a nuclear programme.

2.1.2 Milestone 2

The second phase follows to enact legislation covering all aspects of nuclear safety, nuclear security, safeguards and civil liability for nuclear damage. During Phase 2, the member state should take steps to comply with and establish the framework outlined in Phase 1. When the country is ready to invite bids for the first SMR, Milestone 2 is reached.

2.1.3 Milestone 3

In the final phase, the country is ready to commission and operate its first SMR. Once legislation is in force, legislative oversight should be established to ensure compliance, while maintaining and reviewing the framework during the lifetime of the nuclear power programme. Overall, a key to the success of a national nuclear power programme is *"a competent, effectively independent regulatory body to provide continuing oversight of all facilities and activities, and to enforce continuing compliance with all regulatory requirements"* (International Atomic Energy Agency 2015, 10).

2.2 Small Modular Reactor Deployment Indicators

Table 2-2: SMR Deployment Categories and Indicators

National Energy Demand	SMR Energy Demand	Financial/ Economic Sufficiency	Physical Infrastructure Sufficiency	Climate Change Motivation	Energy Security Motivation
Growth of Economic Activity	Dispersed Energy	Ability to Support New Investments	Electric Grid Capacity	Reduce CO_2 Emissions per Capita	Reduce Energy Imports
Growth Rate of Primary Energy Consumption	Co-Generation	Openness to International Trade	Infrastructure Conditions	Reduce Fossil Fuel-Energy Consumption	Use Domestic Uranium Resources
Per Capita Energy Consumption	Energy Intensive Industries	Fitness for Investment	Land Availability	Achieve NDC Carbon Reduction Goals	Balance Intermittent Renewables

Source: Shropshire and Subki 2018, 7

The IAEA's technical publication on Deployment Indicators for Small Modular Reactors outlines 18 indicators among six categories to assess when considering the adoption and deployment of SMRs *(Table 2-2)*. Reference to SMRs encompasses both sizes – small and micro – unless otherwise noted. The methodology, which targets countries with developing economies and/or no nuclear energy programme, is a starting point to explore the potential for SMR deployment within a country's energy portfolio.

Of the 18 indicators, three reflect the additional benefits and applications provided by SMRs. Furthermore, four indicators, among others, are acknowledged but excluded from further elaboration in the publication, due to lack of data availability *(Table 2-3)*. Some of those indicators, such as electric grid characteristics, could be integrated within the 18 indicators that are established or within the 19 infrastructure issues of the IAEA Milestones Approach.

Table 2-3: SMR-Specific Deployment Indicators

SMR-specific Indicators	Additional/Excluded Indicators
• Dispersed energy • Energy-intensive industries • Co-generation	• Electric grid characteristics • Energy demand forecasts • Number of domestic industries • Technical and regulatory personnel proficiency

The 18 SMR deployment indicators, in addition to the aforementioned indicators that are excluded, are addressed or integrated within the 19 nuclear infrastructure issues of the IAEA Milestones Approach *(Table 2-4)*. By nature of the indicators and relevance to the decision to pursue nuclear energy, many of them are addressed within the infrastructure issue related to the national position.

Table 2-4: SMR Indicators and Infrastructure Issues

18 SMR Deployment Indicators	19 Nuclear Infrastructure Issues
National Energy Demand 1. Growth of Economic Activity 2. Growth Rate of Primary Energy Consumption 3. Per Capita Energy Consumption **SMR Energy Demand** 4. Dispersed Energy 5. Co-Generation 6. Energy Intensive Industries **Financial/Economic Sufficiency** 7. Ability to Support New Investments 8. Openness to International Trade 9. Fitness for Investment **Physical Infrastructure Sufficiency** 10. Electric Grid Capacity 11. Infrastructure Conditions 12. Land Availability **Climate Change Motivation** 13. Reduce CO_2 Emissions per Capita 14. Reduce Fossil Fuel-Energy Consumption 15. Achieve NDC Carbon Reduction Goals **Energy Security Motivation** 16. Reduce Energy Imports 17. Use Domestic Uranium Resources 18. Balance Intermittent Renewables **Additional/Excluded Indicators to Consider** A. Electric grid characteristics B. Number of domestic industries C. Energy demand forecasts D. Technical and regulatory personnel proficiency	1. National position (1, 2, 3, 4, 5, 6, 13, 14, 15, 16, 18, C) 2. Nuclear safety 3. Management 4. Funding and financing (7, 8, 9) 5. Legal framework 6. Safeguards 7. Regulatory framework 8. Radiation protection 9. Electrical grid (10, A) 10. Human resource development (D) 11. Stakeholder involvement 12. Site and supporting facilities (11, 12) 13. Environmental protection (13, 14, 15) 14. Emergency planning 15. Nuclear security 16. Nuclear fuel cycle (17) 17. Radioactive waste management 18. Industrial involvement (B) 19. Procurement

2.2.1 National Energy Demand

Energy demand is an initial driver for consideration and is often linked to growing economic activity and the rate of energy consumption. *"Countries that have high-energy demand growth rates are deemed to be more likely to adopt SMRs than are* *those with stagnant energy demand"* (Shropshire and Subki 2018, 13). Many countries interested in expanding their energy supply are in the throes of development. Energy is considered at the center for supporting the expansion of not only the economy but also surrounding social systems, such as education and health. Coinciding with the nuclear infrastructure issues, results from the national energy demand could be used to inform the IAEA Milestones Approach's national position and vice versa.

Table 2-5 displays the nuclear infrastructure issue in relation to the consideration of SMR and MMR within the first phase of the IAEA Milestones Approach. Some of the main steps or tasks to be completed to address the nuclear infrastructure issue are listed. The complete analysis of the 19 infrastructure issues for each of the three phases is found in Annex 1.

Table 2-5: National Position in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-1. National Position		
1.1. Nuclear power option included in national energy strategy	Yes	Yes
1.2. Nuclear Energy Programme Implementing Organization (NEPIO) established and staffed	Yes	Yes
Activity_M1-1.1: Develop national energy planning for the next 20-30 years **Activity_M1-1.2:** Conduct a pre-feasibility study or develop a comprehensive report covering 19 nuclear infrastructures **Activity_M1-1.3:** International cooperation – IAEA, WANO, reactor technology suppliers, universities, etc.		

Although the indicator – energy demand forecasts – was excluded from the final 18 indicators, demand forecasts could be considered at this stage along with the rate of economic and energy consumption growth.

2.2.2 SMR Energy Demand

The applications specific to SMRs and the benefits that the technology embodies are not a one-size-fits-all solution. SMRs, especially in its early commercial existence, should be recognized and deployed to be mindfully utilized in areas and applications where the benefits can be fully realized. SMRs are particularly attractive to help achieve SDG 7 for energy access, in which areas lacking energy are typically in rural areas that are removed from a central grid. In conjunction with the first category – national energy demand – SMR energy demand should be taken into consideration for the national position. As stated in IAEA guidance, the national position *"should be based on a national energy policy supporting the desired economic development goals of the country and should identify the contribution that nuclear power will make to that policy. (…) if there is an intention to develop nuclear-powered desalination or process heat production, this should also be addressed in the statement"* (International Atomic Energy Agency 2015, 11).

Large nuclear and fossil-fuel plants are often limited to producing electricity. At the same time, an added benefit of SMRs is its co-generation applications, such as process heat, district heating and thermal desalination that can utilize off-peak power. Subsequently, SMRs' residual heat is usable for other industrial applications, such as *"the production of glass, plastics, steel, synthetic fuels and chemicals"* (Shropshire and Subki 2018, 11).

2.2.3 Financial/Economic Sufficiency

Theoretically, the affordability of SMRs, particularly for newcomer countries, puts the technology within closer financial reach. The financial and economic indicators are, once again, reflective of emerging nuclear countries, taking into consideration countries' openness to foreign investment and the ability to obtain financing. The IAEA distinguishes between funding and financing, referring to the former in relation to government responsibility, while the latter refers to the owner's or operator's responsibility.

Table 2-6: Funding and Financing in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-4. Funding and Financing		
4.1. Reactor Cost (Billion USD) – Unit Size Range	0.06 – 2.0	0.02 – 0.15
4.2. Overnight Cost (USD/kWe) • First of a Kind (FOAK) • Nth of a Kind (NOAK)	4,000 to 5,000	4,000
4.3. Levelized Cost of Electricity • First of a Kind (FOAK) • Nth of a Kind (NOAK)	• 65/MWh • 58.5/MWh	• 0.14-0.41/kWh • 0.09-0.33/kW
4.4. Adequate Funding for NEPIO Provided	Yes	Yes
Activity_M1-4.1: Analysis of cost of different SMR/MMR technologies available in the market **Activity_M1-4.2:** Develop a report on strategies for funding and financing for 1) establishing organizations, 2) building nuclear infrastructure and 3) performing activities across all phases of the nuclear power programme		

The extent of government financing will depend on the country's overall economic situation, and for some emerging nuclear countries, financing may be limited. *"A country may seek to reduce the extent to which it must provide financing by engaging local or foreign equity partners who invest directly in the project in exchange for a share in the owner/operator profits or electricity supplied at an agreed price"* (International Atomic Energy Agency 2015, 21).

Though cost estimates widely vary, overnight capital cost estimates for SMRs sit around 4,000 to 5,000/kWe USD, which implies that the levelized cost of electricity (LCOE) *"may be cost competitive with generation from renewables, coal and natural gas, depending on the location"* (Shropshire and Subki 2018, 10). The LCOE provides a holistic measure of the costs that go into the production of a kilowatt-hour, which is levelized over the plant's lifetime. In terms of LCOE, a first-of-a-kind NuScale SMR plant could cost about 65/MWh USD and decline by more than 10 percent for Nth-of-a-kind plants (NuScale Power 2019).

For MMRs, the Nuclear Energy Institute (NEI) estimates that costs for the first MMR will range between *"$0.14/kWh and $0.41/kWh. As companies continue to produce micro-reactors, future costs are estimated to fall between $0.09/kWh and $0.33/kWh"* (Nichol and Desai, Cost Competitiveness of Micro-Reactors for Remote Markets 2019).

In consideration of finances, the entire lifecycle of the SMR, including decommission, should be accounted.

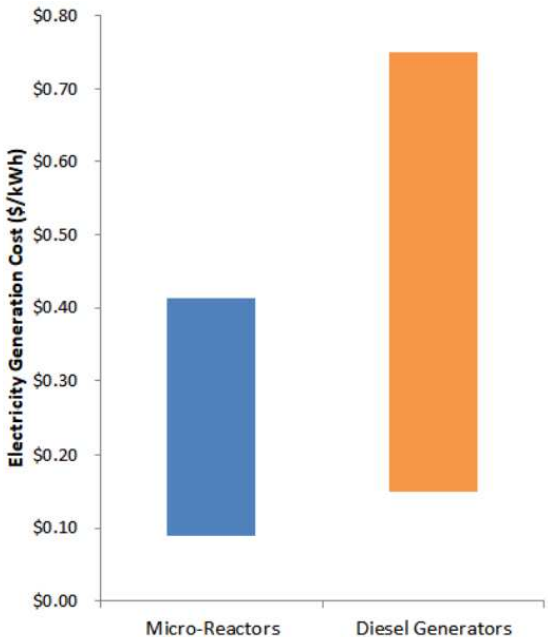


Figure 2-2: Cost of Electricity Comparison (Nichol and Desai, Cost Competitiveness of Micro-Reactors for Remote Markets 2019)

2.2.4 Physical Infrastructure Sufficiency

One of the significant challenges to accelerating access to energy is limited grid coverage in rural areas, and the costs of grid connection for rural electrification are prohibitive. As discussed, a major driver for SMRs is in its flexibility to be installed into an existing grid or remotely off-grid, as a function of its smaller electrical output.

As mentioned, a single power plant should represent no more than 10 percent of the total installed grid capacity, according to the IAEA (International Atomic Energy Agency 2015, 36). This indicator, in addition to the excluded indicator on electric grid characteristics, is of particular interest to countries with less developed infrastructures as the electrical grid's current and planned size and reliability are taken into careful consideration throughout the Milestones Approach.

Table 2-7: Electrical Grid in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-9. Electrical Grid		
9.1. Existing national electrical grid capacity (MWe)	300 – 4000	40 – 300
9.2. Electrical grid status for electricity supply	• On-grid • Isolated grid • Off-grid	• Isolated grid • Off-grid
Activity_M1-9.1: Develop National Electricity System Planning		

Outside direct control of the nuclear industry is the national physical infrastructure needed to support the deployment of the SMR. The foundations for transportation and communication should not be overlooked and should engage a variety of stakeholders for an accurate evaluation.

2.2.5 Climate Change Motivation

The global effort to address climate change and shift the paradigm to clean, sustainable development is addressed within this timely category. Countries looking to expand their energy portfolios have an opportunity to do so with a carbon-free solution in SMRs. To qualify this indicator, looking specifically at a country's motivation will provide a scientific argument in regards to SMRs by analyzing CO_2 emissions and fossil fuel consumption. *"Given that SMRs are both low-carbon emission sources and have energy balancing capability to complement renewable sources, an indicator measuring the reliance on high-carbon fuels is important"* (Shropshire and Subki 2018, 18). The indicator also highlights the role of nuclear power in the fight against climate change.

In the same regard as the first two categories – national energy demand and SMR energy demand – the indicators for climate change would be influential in shaping the national position.

2.2.6 Energy Security Motivation

Within the energy security category, an indicator on domestic uranium resources is of particular interest for countries home to the resource. The indicator scratches the surface of the nuclear fuel cycle – also an infrastructure issue belonging to the Milestones Approach – and brings in a more holistic view that is needed in consideration of SMR deployment. Countries should be able to demonstrate that uranium extraction is economically viable. The IAEA estimates uranium resources to be economically extractable at about 130 USD/kg or less (Shropshire and Subki 2018, 19).

Table 2-8: Nuclear Fuel Cycle in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-16. Nuclear Fuel Cycle		
16.1. Fuel cycle (months)	24 - 48	120 - 360
16.2. Knowledge of nuclear fuel cycle steps and approaches developed	Yes	Not Required
16.3. Need for site spent fuel storage recognized	Yes	Not Required
16.4. Interim spent fuel storage considered	Yes	Not Required
Activity_M1-16.1: Develop a document on national fuel cycle strategy and address non-proliferation issues, regulatory requirements **Activity_M1-16.2:** Develop a document on the importance of the adequate capacity for on-site spent fuel storage, taking into account fuel cycle options		

The IAEA advises countries to *"choose its fuel cycle strategy relatively early, as the choice will influence its selection of a specific nuclear technology"* (International Atomic Energy Agency 2015, 54). The IAEA divides the fuel cycle into two parts: the front end consisting of activities prior to using the fuel and the back end consisting of spent fuel handling and disposal. The extent of the fuel cycle, as practiced with traditional nuclear power programmes, will depend on the design and size of the SMR.

Specifically, some of the MMR designs are intended to eliminate the need for spent fuel storage, which would limit spent fuel handling and disposal to vendors. Vendors would retrieve the reactor vessel, and in principle, countries deploying MMRs will not be required to handle spent fuel locally. For some SMR designs, the eventual goal is to transition them into Generation IV reactors with a closed fuel cycle, in which the fuel element would burn itself.

2.2.7 Additional Indicators

Separately from the 18 SMR deployment indicators, two indicators that were excluded are integrated into the Milestones Approach: the number of domestic industries and personnel proficiency. Under the industrial involvement issue, domestic industries are identified to support the overall operation. *"Industrial capabilities and potentials, including training and development needs,"* should be assessed, and recommended targets should be established *"for short term and long term industrial participation and policies to reach those targets"* (International Atomic Energy Agency 2015, 59).

Table 2-9: Industrial Involvement in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-18. Industrial Involvement		
18.1. Role of industrial involvement	Prominent Role	Not Required *(Unless vendor plans to manufacture MMR in the newcomer country itself)*
18.2. National policy with respect to national and local industrial involvement considered	Yes	
18.3. Need for strict application of quality programmes for nuclear equipment and services recognized	Yes	
Activity_M1-18.1: Develop a strategy for industrial involvement with localization percentage it could achieve		

In regards to personnel proficiency, human resource development is included in the nuclear infrastructure issues. The issue encompasses personnel with skills in management, administration, engineering, etc., to fulfil roles as the regulatory body, owner/operator, technical support and other relevant stakeholders. However, this indicator is highly dependent on the scope and design of the modular reactor. For example, GE Hitachi's water-cooled, natural circulation SMR aims to limit on-site operational personnel to 75 employees (Nuclear Energy Insider 2018), while each NuScale SMR plant will employ about 300 people (NUCLEUS, NuScale Power 2019). Supporting personnel proficiency, *"both initially and in the longer term, will depend on the balance the country chooses between engaging foreign expertise and building up its own expertise, and how quickly it plans to shift that balance over time"* (International Atomic Energy Agency 2015, 38). On the other hand, some SMR and MMR design features do not require on-site personnel but instead enables a remote workforce and remote operations, which could pose different opportunities and challenges to human resources.

In light of the nuclear industry's efforts to cultivate gender parity, the burgeoning field of SMRs is an opportunity to address the issue and to integrate measures within the development of guidance and initiatives surrounding SMRs. Even within the adaptation of the SMR and MMR roadmaps, the scope of human resource development should be widened to target the increase of women in the nuclear industry. Shortly after taking office in December 2019, the IAEA Director General Rafael Mariano Grossi launched the Marie Skłodowska-Curie Fellowship Programme to encourage and support more women in nuclear. *"Women are still far from being adequately represented in the nuclear field, and this is unacceptable,"* Grossi stated at the launch of the fellowship programme in March 2020 (IAEA Press Office 2020).

Table 2-10: Human Resource Development in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-10. Human Resource Development		
10.1. Workfoce required for operation	60 - 375	15 - 50
10.2. Necessary knowledge and skills identified	Yes	Yes
10.3. Develop and maintenance of human resource base planned	Yes	Yes
Activity_M1-11.1: Develop a human resource development plan for future organizations with organization structure, roles and responsibilities, workforce required, recruitment, training and managing human resource across each phase		

Radioactive waste management is not distinctly discussed in the SMR deployment indicators but is raised within the infrastructure issues. Because waste management is a major concern and factor in the deployment of nuclear energy, radioactive waste – though significantly reduced or eliminated in SMRs and MMRs – should be addressed to provide a full outlook and holistic approach to SMR deployment. Similar to the treatment of the nuclear fuel cycle, the type and design of the SMR will influence the extent of requirements and needs for waste management. For MMRs and some SMRs, it is expected that vendors will be mostly responsible for waste management. For other SMRs, deploying countries will have to ensure that the adequate infrastructure, regulatory framework and capabilities are readily available to handle this new form of waste for the country.

Table 2-11: Radioactive Waste in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-17. Radioactive Waste Management		
17.1. Radioactive waste management	• On-Site Storage • Off-Site Facility	Off-Site Facility
17.2. Burdens of radioactive waste recognized	Yes	Yes
17.3. Review capabilities for waste processing, storage and disposal	Yes	Not Required
17.4. Options for ultimate disposal of high-level radioactive waste	Yes	Not Required
Activity_M1-17.1: Develop a document on significant implications of radioactive waste, need for national capabilities, regulatory framework, financing scheme and infrastructure for radioactive waste management.		

2.3 The 3S Concept – Safeguards, Safety and Security

The triumvirate of safeguards, safety and security (3S) prevails throughout the lifecycle of a nuclear power programme, from the conception, design and deployment to operations and decommissioning. The 3S share a balance of intrinsic (technical and instrumentation features) and extrinsic (administrative or procedural commitments) measures to ensure successful operations, and they represent three disciplines driven by different motivations and stakeholders *(Table 2-12)*. The 3S concept recognizes overlaps in terms of tools of implementation, as well as regulations. Measures that address one of the three elements can help address the other complementing elements. For example, a measure to secure nuclear material will ensure the safe use of the material, while also protecting it against non-peaceful uses.

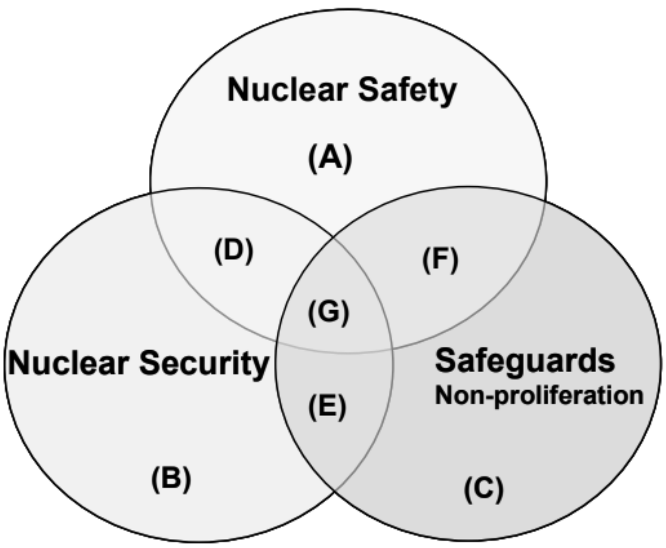
Table 2-12: Safeguards, Safety and Security Defined

Safeguards	Safety	Security
• Verification that nuclear facilities and materials are not misused or diverted from peaceful uses	• Prevention of accidents and protection of humans and the surrounding environment	• Prevention of illegal or malicious acts involving nuclear material and associated facilities
• Responsible stakeholder: IAEA	• Responsible stakeholder: National, local authorities	• Responsible stakeholder: National, local authorities
The 3S Concept Synergies and interrelations among safeguards, safety and security are recognized to prevent gaps, inconsistencies and redundancies. The consolidation of activities optimizes operations and costs.		

This chapter reveals how the development of SMRs has so far – to a limited extent – integrated the 3S concept and how collaboration on the concept between 3S authorities, regulators and designers could positively impact future SMR regulatory effectiveness and operational efficiency.

2.3.1 History of the 3S Concept

In an effort to assist countries embarking on nuclear power programmes, in 2008, G8 leaders representing Canada, the European Commission, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States launched the International Initiative on 3S-Based Nuclear Energy Infrastructure to underline *"the paramount importance of nuclear non-proliferation/safeguards, safety and security in the peaceful uses of nuclear energy (...) recognizing that ensuring 3S forms a sound basis for international transparency and confidence in the sustainable use of nuclear energy"* (G8 Summit 2008). The initiative highlights the interrelations among safeguards, safety and security, particularly related to supporting infrastructure development *(Figure 2-3)*.



(A) Emergency core cooling system for nuclear power plant, (B) Barrier at the facility entrance, (C) Authenticated apparatus

(D) Double-entry doors to keep negative pressure and prevent radioactive release
(E) Management of nuclear material using containment and surveillance and remote monitoring camera
(F) Management of nuclear material for criticality and accounting control

(G) Possible monitoring camera for multipurpose use, such as joint use of equipment

Figure 2-3: Synergies of the 3S - Safeguards, Safety and Security (Suzuki, et al. 2010)

Shortly after the launch of the 3S initiative, the Japan Atomic Energy Agency conducted a gap analysis to identify overlaps in order to capitalize on synergies and efficiencies. The study's initial outcome realized that differences among the individual "S" communities hinder the synergetic effects because of inherent silos between them. The study also found that *"incorporation of 3S synergism into the conceptual design and system development phase increases regulatory effectiveness, as well as operational efficiency, and also reduces expensive and time-consuming retrofitting"* (Suzuki, et al. 2010).

2.3.2 The 3S by Design

Lessons learned from Chernobyl and Fukushima accidents are incorporated into mandatory requirements of any reactor design, large or small. To date, the IAEA does not plan to develop SMR-specific safety standards but will produce a *"tailor-made solution to help national authorities regulate this new class of nuclear power reactors"* (Broussard 2020). Separately, the IAEA also concluded that existing nuclear security guidance remains valid for known concerns related to SMRs. *"The keyword is known. The fact of the matter is you don't know what you don't know,"* said a Senior Nuclear Security Officer at the IAEA. *"There are challenges to SMRs that we're just not aware of, but we believe that we are covered with the existing nuclear security guidance for both SMRs and TNPPs (transportable nuclear power plants)"* (IAEA Division of Nuclear Security 2019).

From a safety perspective, SMRs emphasize inherent safety features better than existing nuclear power plants. SMRs are designed to be all-encompassing, with the fuel, steam and generator components housed all in one vessel. *"This reduces the risk of accidents because there are less pipes to break,"* José Reyes, NuScale co-founder and chief technology officer, said in an article published by the Yale School of Forestry and Environmental Studies(Parshley 2020). The inherent safety features of SMRs demonstrate the engineering approach related to safety by design, a method that is becoming prevalent to safeguards and security, as well. *"There is an early recognition that a formal engineering approach is required for security and safeguard design, as is already commonly adopted for safety systems,"* said Bhaskar Sur, Director of the Safety and Security S&T Program at Canadian Nuclear Laboratories, at the International Conference on Nuclear Security (ICONS) at the IAEA, 10-14 February 2020. Given the interlinks and the established demonstration of fulfilling one of three pillars with a by-design approach, early consideration in the design process would allow for optimal confluence and efforts to address the three essential infrastructure issues to SMR deployment and operation.

On the security side, Dan Hasted, UK Office for Nuclear Regulation Superintending Inspector, urged participants at the 2020 ICONS to shift the perception of security from being a factor of cost to being a measure to reduce costs. Integrating security from the start sets the foundation for more accurate cost and schedule forecasts. *"If we do not achieve security by design, the security that we have to retrofit would be more expensive. It will be more difficult to maintain, need more human interaction rather than having passive engineering. Having security by design can reduce the lifetime physical protection costs, both the capital expenditure and the operational expenditure"* (Hasted 2020).

Safeguards by design has been an approach considered and well addressed by the non-proliferation community. The IAEA has published a series of guidance that applies the concept, *"from initial planning and design through construction, operation, spent fuel management and decommissioning"* (International Atomic Energy Agency 2020a). In a similar vein to safety by design and security by design, the goal of safeguards by design is *"to facilitate safeguardability of new nuclear installations that allows for efficient and effective application of safeguards measures (systems and processes) with reduced impact on the facility operation"* (Stein and Morichi 2012).

Early engagement allows for the 3S to be integrated into the design process, where designers have sufficient guidance and requirements, provided by stakeholders, to facilitate the design of modular reactors with minimal, if any, impact on the operation. By integrating the 3S, and thus realizing their synergies, the SMR community has a unique opportunity to adopt the 3S by design (3SBD) approach, which *"increases regulatory effectiveness as well as operational efficiency, and also reduces expensive and time-consuming retrofitting"* (Suzuki, et al. 2010). The approach places the onus upon the deliberate interaction of relevant stakeholders – 3S authorities, regulatory authorities, designers and operators.

Each of the three concepts utilizes instrumentation, such as video surveillance, which has potential *"to be jointly managed by single measurement systems and the generated information to be shared among the stakeholders involved"* (Stein and Morichi 2012). Furthermore, the consolidation of data could lead to savings on installation and real estate. *"Combining such measures with modern data* *communication schemes, such as remote monitoring, will further reduce the need for inspectors to spend time-consuming IAEA technician visits"* (Stein and Morichi 2012).

Logistically, transporting nuclear material for installation in remote locations is a challenge, but *"a robust engineering approach with controls built into the design can offer reduced uncertainties and costs associated with complex transportation issues for SMRs,"* Sur said (2020). The physically remote nature of some SMRs and MMRs, an added benefit – and challenge – *"is in the limited consequences of ecological release and the limited access for launching an attack,"* Sur explained (2020).

Given that SMRs have far less nuclear fuel, simpler systems and passive safety features, the emergency planning zone (EPZ) could be much smaller than what is acceptable for conventional nuclear power plants. *"Large nuclear reactors have a 'plume exposure pathway' EPZ, which is about 10 miles (16 km), and a larger 'ingestion exposure pathway' EPZ, which, depending on the country, is typically about 50 miles (80.5 km) from the site"* (Zabielski 2018). The plume exposure pathway is designed to avoid or reduce the dose from exposure to radioactive material. In contrast, the ingestion exposure pathway is designed to avoid or reduce the dose that could be ingested via food or water sources. NuScale Power worked with the NEI to develop a methodology to determine the EPZ for its SMRs. They concluded that the EPZ could be hundreds of times smaller and reduced to the plant site boundary of about 40 acres (NuScale Power 2020c).

Table 2-13: Emergency Planning in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-14. Emergency Planning		
14.1. Exclusion zone	Site Boundary	Site Boundary
14.2. Appreciation of the need for emergency planning, developed	Yes	Yes
14.3. Communication with and involvement of local and national government taken into account	Yes	Yes
14.4. Emergency planning for existing radiation facilities and practices	Yes	Yes
Activity_M1-14.1: Develop a plan for environmental issues		

Aside from the physical risks, cybersecurity – protection of computer systems and networks – is another issue that must be addressed in the design of SMRs. Passive safety and fail-safe features enable remote human resources and remote operations. *"The adoption of a strong cybersecurity program at the very beginning of the design stage of SMRs, for remote monitoring and lowering the operating manpower requirements, cannot be overstated,"* Sur said (2020).

2.3.3 The 3S in International Legal Guidance

The 3S concept has further implications in nuclear-related legislation, and conversely, legislation dictates the direction of 3S. Many nations have laws related to utilizing radiation sources for medical, agricultural and industrial practices but lack legislation needed for ionizing radiation for nuclear power. In nuclear law, the 3S concept provides general guidance that *"emphasizes the interrelations between the fields of safety, security and safeguards, including the need for legislation to reflect such interrelations in a comprehensive and synergetic manner"* (Stoiber, et al. 2010, 2).

Nuclear law aims to support member states in adopting *"national legislation that implements their obligations under relevant international instruments (conventions, treaties, agreements, United Nations Security Council resolutions) to which they have become a Party or are otherwise bound under international law"* (Stoiber, et al. 2010, 7). That said, international instruments have been refined to cover different aspects of a nuclear power programme, such as waste management safety, nuclear liability and safety of civil nuclear power reactors, to help harmonize national nuclear laws. As a form of civil nuclear power, existing international instruments are fundamental in ensuring the safe and peaceful use of SMR technology.

In the interest of newcomer countries, preparing the legal basis for the deployment and operation of SMRs should begin during Phase 1 of the roadmap to deployment. Essentially, modular reactors will be subject to the same jurisdiction as their larger counterparts. Under safeguards, the main activity is to develop a plan approved by the national government to adhere to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the Comprehensive Safeguards Agreement *(Table 2-14)*. The newcomer country should consult with international organizations in the safety and security sphere, and join the Convention on Nuclear Safety. A technology assessment of the selected SMR will determine specific needs and actions related to safety and security measures that will shape further legislative and operational matters.

Table 2-14: Nuclear Safeguards, Security and Safety in Consideration of SMR and MMR

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme		
Nuclear Infrastructure	**Small Modular Reactor (SMR)**	**Micro Modular Reactor (MMR)**
M1-6. Safeguards		
6.1. Obligations under NPT and non-proliferation treaties and other international instruments, recognized	Yes	Yes
6.2. Development, implementation and enforcement of safeguards framework, including SSAC establishment, planned	Yes	Yes
Activity_M1-6.1: Develop a plan approved by the government to adhere to NPT and Comprehensive Safeguards Agreement		
M1-2. Nuclear Safety		
2.1. SMR/MMR utilization	• National electricity supply • Mining and heavy industry • Water desalination • District heating • Hydrogen production • Rural/remote electrification • Island electrification	• Rural/remote electrification • Island electrification • Mining and heavy industry • Water desalination • District heating • Hydrogen production
2.2. Unit size (MWe)	10 – 300	< 10
2.3. Typical plant output (MWe)	100 – 600	4 – 100
2.4. Plant life (years)	60	10 - 30
2.5. Core damage frequency		
Activity_M1-2.1: Conduct SMR technology assessment **Activity_M1-2.2:** Join Convention on Nuclear Safety and cooperate with international organizations on nuclear safety		
M1-15. Nuclear Security		
15.1. Requirements for security and physical protection acknowledged	Yes	Yes
15.2. Necessary regulation identified	Yes	Yes
15.3. Effective security protection for existing uses of radiation sources	Yes	Yes
Activity_M1-15.1: Develop a plan for nuclear security – policy, roles, structure, responsibilities and reporting requirements **Activity_M1-15.2:** Plan to develop national legislation providing a basis for regulation of security and physical protection arrangements regarding nuclear facilities, nuclear and other radioactive material, its transportation and storage, including provisions for licensing, inspection and sanctions		

One of the main points made in the IAEA's *Handbook on Nuclear Law* is that each member state must tailor its framework, taking into consideration its cultural traditions, scientific, technical and industrial capacities, as well as financial and human resources. This consideration should also be applied to the type of SMR technology being deployed. While the infrastructure needs for SMRs are similar to those of a nuclear power plant, the smaller scale of SMRs requires an infrastructure of the same scope but, potentially, to a lesser extent, which allows member states to take a graded approach to tailor elements to SMR requirements. NuScale, among other vendors, has justified that because modular reactors can be sited underground and contain smaller quantities of radioactive materials, risks are reduced and, for example, would demand different security measures and potentially fewer security staff (Parshley 2020).

2.4 International Legal Instruments

The IAEA has adopted 12 legal instruments relevant to the establishment of a nuclear power programme. The legal instruments address the peaceful uses of nuclear energy and are comprised of legally binding conventions or agreements related to safety, security and liability. By adopting these instruments, a member state of the IAEA would enter into treaty relations with other member states and would be bound to uphold and fulfil its responsibilities.

Three of the four safety-related conventions were adopted in the aftermath of the 1986 Chernobyl nuclear plant accident. Table 2-15 provides an overview of the legal instruments and how they are relevant to the deployment and operation of SMRs.

Table 2-15: Summary of Legal Instruments

About the Legal Instrument	Relevancy to SMRs/MMRs
Convention on Early Notification of a Nuclear Accident	
• Entered into force in October 1986, following a special session after the Chernobyl accident • Requires member states to *"notify, directly or through the International Atomic Energy Agency, those States which are or may be physically affected (…) and the Agency of the nuclear accident, its nature, the time of its occurrence and its exact location where appropriate"* (Convention on Early Notification of a Nuclear Accident 1986, Art. 2).	Applicable to SMRs, as Article 1 defines a broad scope of its application to cover: *(a) any nuclear reactor wherever located;* *(b) any nuclear fuel cycle facility;* *(c) any radioactive waste management facility;* *(d) the transport and storage of nuclear fuels or radioactive wastes;* *(e) the manufacture, use, storage, disposal and transport of radioisotopes for agricultural, industrial, medical and related scientific and research purposes; and* *(f) the use of radioisotopes for power generation in space objects*(Convention on Early Notification of a Nuclear Accident 1986, Art. 1).
Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency	
• Entered into force in February 1987, made in response to the Chernobyl accident • Outlines a framework for cooperation "*to facilitate prompt assistance in the event of a nuclear accident or*	Should an incident occur in the development, transportation, installation, operation, decommissioning, etc., of the SMR unit or plant, the swift cooperation of member states and the IAEA to address the accident will be necessary.

About the Legal Instrument	Relevancy to SMRs/MMRs
radiological emergency to minimize its consequences and to protect life, property and the environment from the effects of radioactive releases" (Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency 1986, Art. 1).	
Convention on Nuclear Safety	
• Entered into force in October 1996, made in direct response to the Three Mile Island and Chernobyl accidents. • First international treaty to address the safety of nuclear installations. • Three objectives: - To maintain nuclear safety through national measures and international cooperation - To maintain defenses in nuclear installations against radiological hazards to protect society and the environment - To prevent accidents and to mitigate consequences (Convention on Nuclear Safety 1994, Art. 1).	Concerning the safety of installations, Articles 17 and 18 refer to siting, design and construction. The scale of SMRs simplifies some issues, such as siting – the selection and evaluation of a site for nuclear installation – as well as construction, since SMRs are fabricated off-site and delivered as a single module. By design, inherent safety features of the SMR addresses some of the safety-related articles found in the convention.
Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	
• Entered into force in June 2001. • Addresses spent fuel and radioactive waste management safety by establishing safety principles.	For SMRs, the amount of and movement of spent fuel and radioactive waste is significantly less than the average nuclear power plant. The SMR module would be changed after a number of years, at which time the reactor module would be returned to the vendor. The need for spent fuel storage on-site, as well as interim spent fuel storage, would be limited for SMRs or not needed for MMRs. Regulating the movement of spent fuel is of particular interest, as modules are likely to be transported from one member state to another's site location. Article 27 addresses transboundary movement, which holds states accountable to take steps *"to ensure that such movement is undertaken in a manner consistent with the provisions of this Convention and relevant binding international instruments"* (Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management 1997).
Convention on the Physical Protection of Nuclear Material and Amendment	
• Entered into force in February 1987 and was further amended in July 2005 to strengthen its provisions. • Covers the physical protection of nuclear material during international transport and establishes a framework for member states to cooperate to	The movement of nuclear material from vendors to site locations will require measures – by design and processes - to ensure the safe and secure transport of modular reactors. With the introduction and adoption of nuclear power, the measures to protect nuclear material must be well established within newcomer states.

About the Legal Instrument	Relevancy to SMRs/MMRs
recover and return stolen material (Convention on the Physical Protection of Nuclear Material 1980).	
Vienna Convention on Civil Liability for Nuclear Damage	
• Entered into force in November 1977, one of three instruments related to liability. • Established minimum standards for financial protection against damages that may incur from utilizing nuclear energy.	Ensures that each member state has regulations in place that conform to the legal regime for civil liability for nuclear damage. Nuclear damage is defined as a *"loss of life, any personal injury or any loss of, or damage to, property which arises out of or results from the radioactive properties (...) or other hazardous properties of nuclear fuel or radioactive products or waste in, or of nuclear material coming from, originating in, or sent to, a nuclear installation"* (Vienna Convention on Civil Liability for Nuclear Damage 1963, Art. 1).
Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage	
• Entered into force in October 2003. • Increases the liability of the nuclear installation's operator and increasing means to secure compensation (Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage 1997).	For SMRs and MMRs, it will be necessary for emerging nuclear countries to understand the associated liabilities and establish who – the vendor or deploying country – is liable for potential damages.
Convention on Supplementary Compensation for Nuclear Damage	
• Entered into force in April 2015. • Established a minimum amount of national compensation and increases the amount of compensation available through a global public fund in case the national amount is insufficient (Convention on Supplementary Compensation for Nuclear Damage 1979).	This convention could be of particular importance for emerging countries that are budget constrained. The IAEA developed a calculator available online, which applies Article IV of the Convention, to estimate the amount member states would contribute to the international fund.
Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention	
• Entered into force in April 1992. • Establishes a bridge between member states that are party to the Vienna Convention and member states that are party to the Paris Convention. The conventions reflect similar legal regimes of civil liability, but member states that are party to one convention are not party to the other (Joint Protocol Relating to the Application of the Vienna Convention 1988).	The Joint Protocol is essential in resolving issues related to determining the liability of the operator and jurisdiction in transport cases while extending the mutual benefits of both conventions.
Comprehensive Safeguards Agreement	
• Prevents the spread of nuclear weapons and to promote cooperation for peaceful uses of nuclear energy.	The member states' obligations mainly shape the legal framework for safeguards under the NPT. These treaties establish nuclear-weapon-free zones and other safeguard instruments, such as agreements, protocols and subsidiary

About the Legal Instrument	Relevancy to SMRs/MMRs
	arrangements. Nearly all countries – developed and developing – are party to the treaty, except for India, Pakistan and Israel.
Additional Protocol	
• Provides additional tools for verification and increases the IAEA's ability to verify the peaceful use of nuclear material.	The limited supply of nuclear material existing in emerging countries and the smaller amounts necessary for SMRs will be sufficiently covered.
Revised Supplementary Agreement Concerning the Provision of Technical Assistance	
• Provides the member state with technical assistance provided by the IAEA.	The Agreement stipulates that the technical assistance countries receive is to be *"used only for peaceful applications of atomic energy and (...) shall not be used for the manufacture of nuclear weapons, for the furtherance of any military purpose and for uses which could contribute to the proliferation of nuclear weapons"*(Revised Supplementary Agreement Concerning the Provision of Technical Assistance - Model Text 2016, Art. 3).

2.5 Proposed Deployment Roadmaps for Small and Micro Modular Reactors

The roadmaps for SMR and MMR deployment in Figures 2-4 and 2-5, respectively, reflect a summary of the adaptation of the IAEA Milestones Approach. Based on the aforementioned SMR deployment indicators, the 3S concept and further subject-matter expert input, each of the 19 infrastructures was evaluated in the context of SMRs and MMRs. A broad approach was applied to the analysis, since the specific design of the SMR or MMR will heavily influence some issues. The Annex provides the complete analysis of the 19 nuclear infrastructure issues throughout the three phases of the original IAEA Milestones Approach.

While the time from initial consideration of a conventional nuclear power plant to launching operations is about 10 to 15 years, the time for SMR deployment could range from 7 to 10 years, and even less for MMRs at 4 to 7 years. The scale of modular reactors simplifies some infrastructure issues, such as siting – the selection and evaluation of a nuclear installation site – which would likely influence timing, costs, public acceptance and safety of the installation in a favourable way. The suggested timing is reminiscent of industry sentiment toward deployment for defense installations, in which the NEI estimated a MMR could be deployed in 7 years by 2027 *(Figure 2-6)*. *"Microreactors can be deployed much more quickly than nuclear reactors (...) There's a lot of opportunity to accelerate this schedule. We were conservative and had our NRC licensing at three years. We think it can be done faster than that for microreactors and* *even the manufacturing and construction time we think can be done a lot faster,"* said Marc Nichol, Senior Director of New Reactors at the NEI (Nichol, Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations 2018).

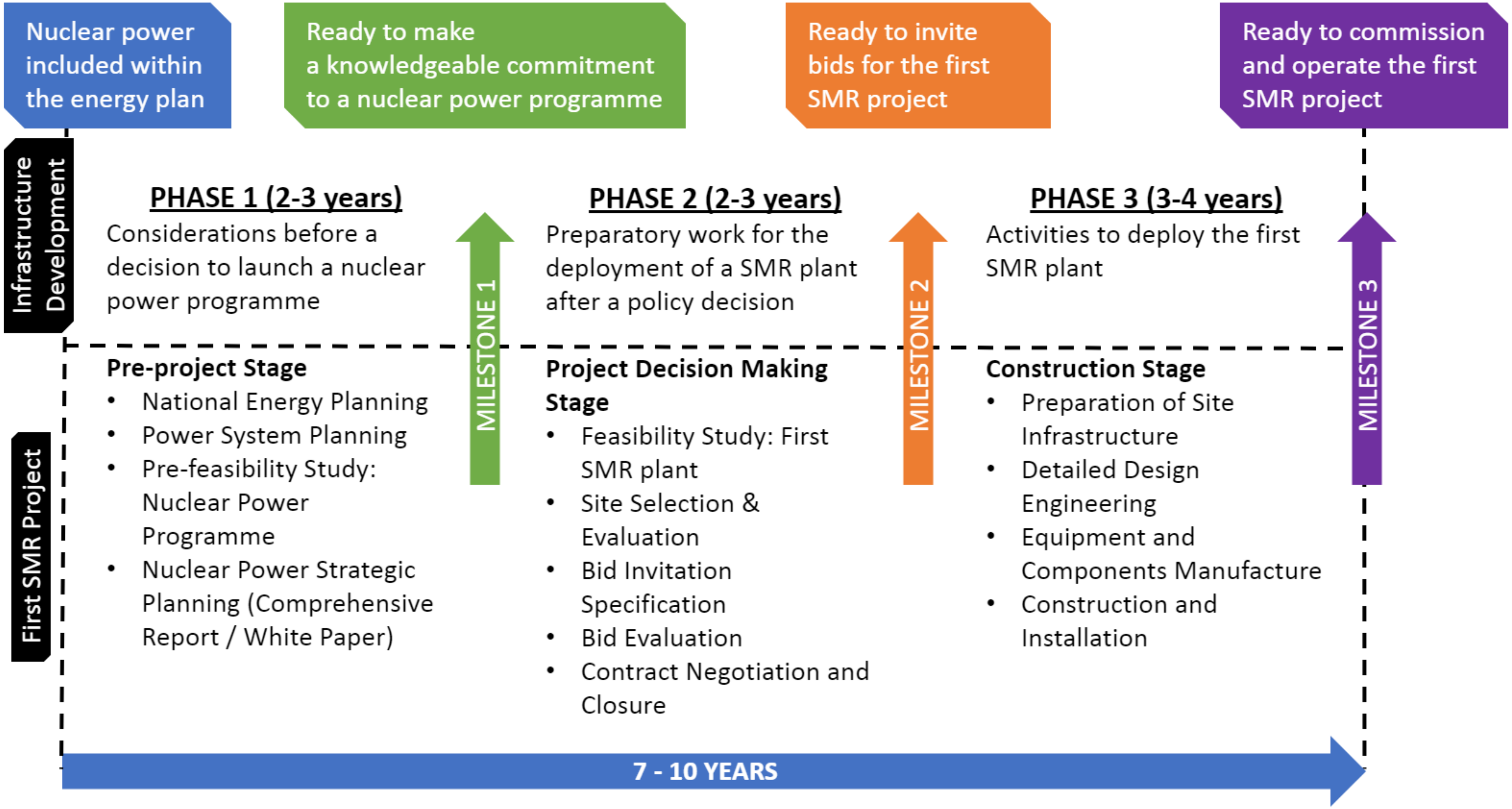


Figure 2-4: Roadmap for SMR Deployment in a Newcomer Country

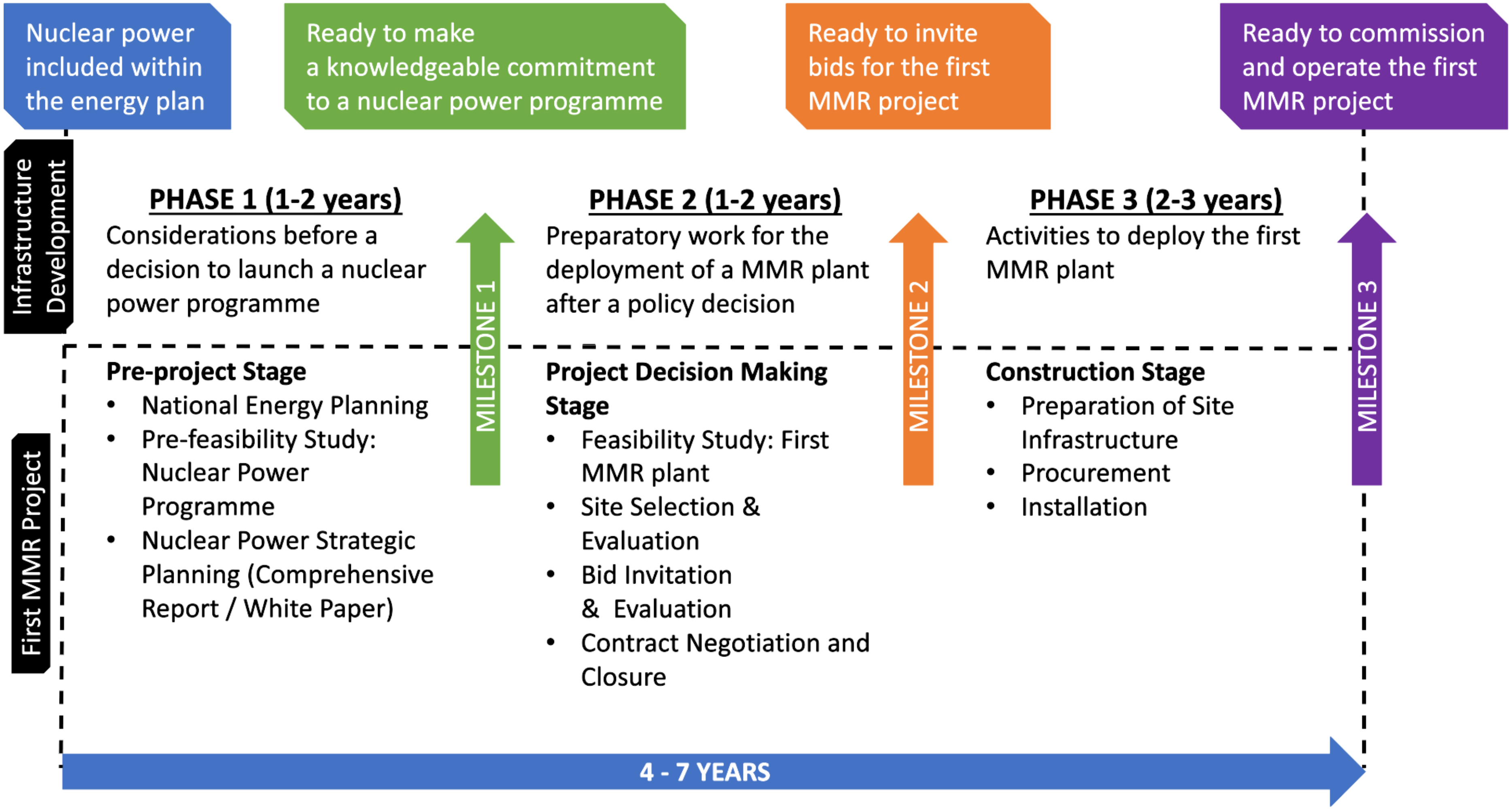


Figure 2-5: Roadmap for MMR Deployment in a Newcomer Country

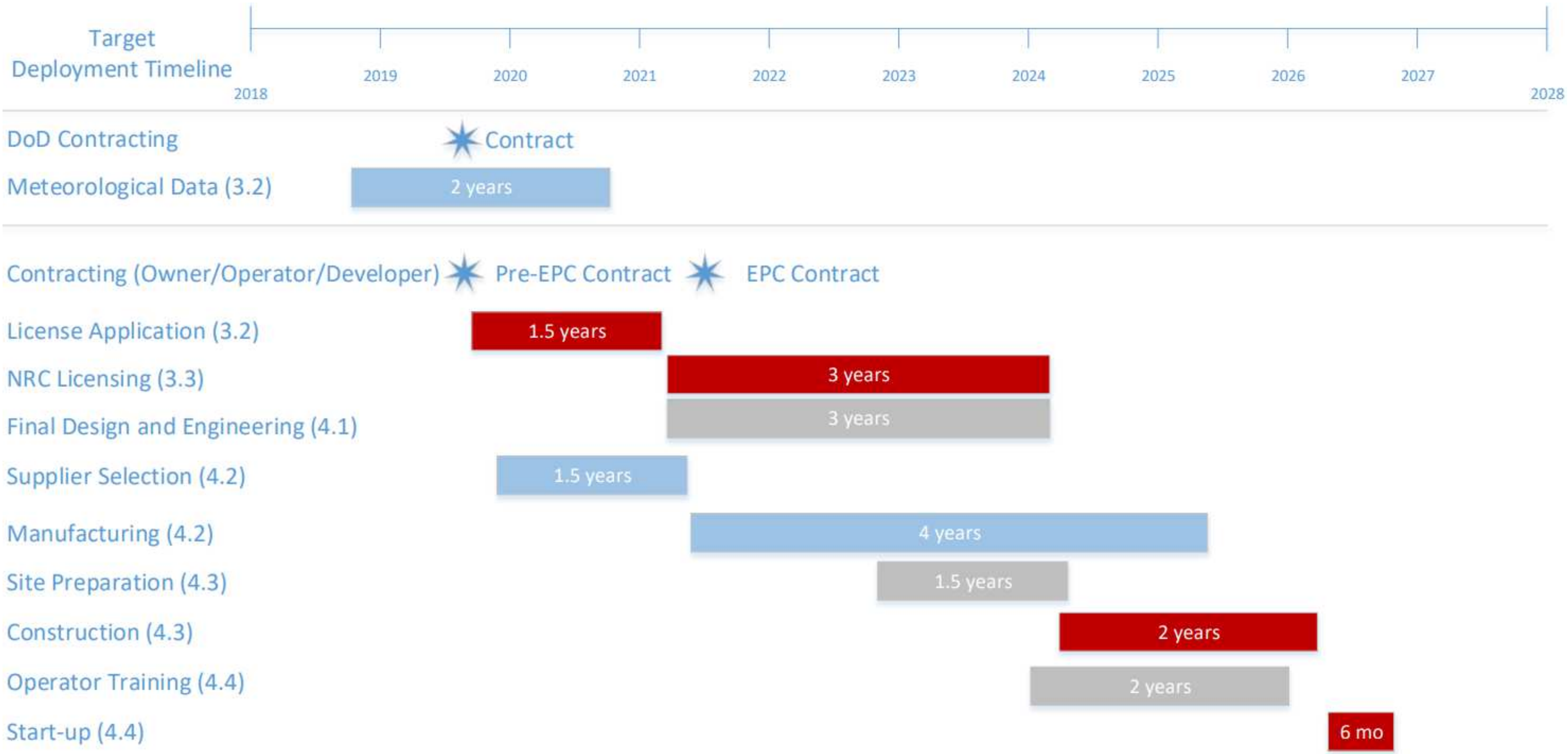


Figure 2-6: Timeline for the Deployment of Micro Reactors for U.S. Department of Defense Domestic Installations (Nichol, Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations 2018)

3. Case Study – Tanzania

Despite possessing a range of energy resources – from hydropower in the central regions and offshore oil and gas reserves in the east and west – the power sector in sub-Saharan countries of Africa remains underdeveloped. There are many countries with exceptional deficits in energy access. Currently utilized fossil-fuelled power plants not only pollute the environment but are challenged with underdeveloped transportation and pipeline infrastructure to deliver the required fuel to operate existing plants. There is a significant interest in commercial nuclear power in several sub-Saharan African countries, matched with the potential for nuclear power to provide emission-free, baseload energy to meet current and future demand. As discussed in Section 2.2.4, grid capacity is a major infrastructure issue, lending more reason to argue for SMRs over conventional nuclear power plants in these emerging nuclear newcomer countries. About one-third of the 30 countries considering nuclear power are in Africa, including Tanzania (World Nuclear Association 2020a). The case study assesses Tanzania's energy demand and plans for energy development in relation to limited grid capacity and the potential for SMRs and MMRs to contribute to a sustainable, clean energy solution. The deployment potential of SMRs and MMRs will be evaluated as an alternative to fossil-fuelled sources of energy.

3.1 Country Overview

The United Republic of Tanzania (Tanzania) borders the Indian Ocean between Kenya and Uganda to the North; Rwanda, Burundi and the Democratic Republic of Congo to the West; and Zambia, Malawi and Mozambique to the South. Tanzania is home to the largest population in East Africa – about 54.66 million – and has the lowest population density *(Table 3-1).* Though the majority of the country's population resides in rural areas, electrification in rural areas was about 17 percent in 2017, according to the CIA World Fact Book (Central Intelligence Agency 2020). In terms of electricity access, the World Bank ranks Tanzania in the

Figure 3-1: Map of Tanzania
(Central Intelligence Agency 2020)

bottom 20th percentile of countries (World Bank Group 2019). The country's energy deficit is linked to the limited generation capacity, which is primarily linked to a lack of large-scale investment. Access to reliable and affordable energy – SDG 7 – is paramount to the development and economic growth. Energy is often acknowledged as an outstanding bottleneck and limiting factor that constrains social and industrial productivity.

Table 3-1: Overview of Tanzania

Profile of the United Republic of Tanzania (2017 estimates unless otherwise noted)	
Population	54.66 million (about 2/3 rural)
Population without Electricity	39 million
Electrification	• Total Population: 33 % • Urban areas: 65 % • Rural areas: 17 %
Electricity	• Installed generating capacity: 1.457 million KW* 55 % from fossil fuels* 40 % from hydroelectric plants 6 % from other renewable sources • Production: 6.699 billion kWh* • Consumption: 5.682 billion kWh* Per Capita: 102.5kWh* • Exports: 0 kWh* • Imports: 102 million kWh*
CO_2 Emissions	0.22 tCO_2/capita
Price of Electricity	13.3 cents USD/kWh
GDP	162.5 billion USD • Per Capita: 3,200 USD • Composition, by sector of origin: Agriculture: 23.4% Industry: 28.6% Services: 47.6%
Labor force**	• Agriculture: 66.9% • Industry: 6.4% • Services: 26.6%
Climate	Tropical along the coast, temperate in the highlands
Natural hazards	Flooding, drought
2016 estimates* * 2014 estimates* *Source: Central Intelligence Agency 2020 and World Bank Group 2019*	

The country's majority reliance on fossil fuels is detrimental to the health of its population and environment. The principal source of electricity generation is fossil fuels, and some of the major environmental and health issues are related to water pollution and indoor air pollution *"caused by the burning of fuel wood or charcoal for cooking and heating"* (Central Intelligence Agency 2020).

In 2003, Tanzania's Atomic Energy Act No.7 established the Tanzania Atomic Energy Commission (TAEC) as the official branch of government responsible for all matters related to the application of atomic energy. The commission is responsible for three main objectives:

1. *Control of the peaceful uses of nuclear technology*
2. *Promotion of the peaceful application of nuclear technology and atomic energy and*
3. *Advising the URT Government on matters pertaining to the International Atomic Energy Agency (IAEA) and all the entailing conventions and agreements on nuclear energy and atomic energy* (Tanzania Atomic Energy Commission - Our Work 2017).

The TAEC replaced Tanzania's National Radiation Commission, which was established in 1983. Tanzania does not have a nuclear power program. However, the TAEC's mandate provides the opportunity for the *"development or practical applications of atomic energy and nuclear technology for safe and peaceful purposes, including the production of electric power using nuclear reactors, with due consideration of the safety and needs of the nation"* (Tanzania Atomic Energy Commission - Our Work 2017).

3.1.1 Nuclear Activity

Tanzania has a long history of utilizing nuclear applications. Since the late-1940s, the country began to use nuclear technology in the medical field (Busagala 2020), creating an environment familiar with nuclear applications and a basis for the legal framework necessary for potential nuclear power operation. *"There are 944 users of nuclear technology in the country; hence rises the need of having efficient and effective regulatory infrastructure for the safety, security and safeguards of nuclear materials,"* said Lazaro Busagala, Director General of the TAEC, at the 2020 ICONS side event on regional cooperation on security, safety and safeguards in Africa.

In cooperation with the European Commission, to support Tanzania's regulatory authority, the TAEC has hosted workshops, training courses and expert missions to boost the capacity and capability of nuclear safety and security (Busagala 2020). In a separate project focused on the 3S infrastructure, the TAEC hosted 40 people from seven different authorities within Tanzania for training on the nuclear 3S aspects.

Tanzania is also acquiring equipment and constructing a laboratory, which will become a training center for nuclear technology to serve the East Africa region. The laboratory's construction is expected to be completed by the end of 2020 (Busagala 2020). The TAEC's 1st Annual Conference and Exhibitions on Nuclear Science and Technology Applications, including energy production, was scheduled to take place in June 2020 but was postponed due to the coronavirus pandemic.

In addition to nuclear applications, Tanzania will commence its first uranium mining operations, contingent on a favorable uranium market. Tanzania has known uranium deposits of 50,000 tons (Busagala 2020). The Mkuju River Project, located in southern Tanzania, is the country's first approved mining site. According to the IAEA, once in operation, the project is expected to produce 1,400 tons of uranium annually (Dixit 2018).

3.2 Power System Master Plan

From June 2014 to December 2016, Tanzania conducted a comprehensive study to produce the Power System Master Plan (PSMP). The study assesses projected energy demand and options to meet such demand in order to guide the development of Tanzania's power system to 2040. The goal of the PSMP is to provide access to electricity to all and to cultivate socio-economic development. Although nuclear power generation is identified as a possible option in the future, it is not considered in the PSMP. Given the long-term goal of reaching 100 percent electrification by 2040 and the rate of development of modular reactor technology, there is potential for SMRs and MMRs to contribute to achieving universal access to electricity by 2040 and beyond.

The Ministry of Energy and Minerals, in collaboration with the National Bureau of Statistics, Rural Energy Agency, Tanzania Electric Supply Company (TANESCO), Japan International Cooperation Agency, etc., proposed six different scenarios for energy generation *(Table 3-2)* and set an ambitious target of reaching 75 percent electrification of households by 2035 and 100 percent electrification by 2040, up from 33 percent in 2015 (Ministry of Energy and Minerals 2016). The potential generation capacity from each energy resource – gas, coal, hydro and renewables – provides the basis for the scenarios, and the diverse mix prevents reliance on a single energy source. The plan also takes into consideration the sustainability and environmental aspects of power generation.

"Considering various aspects, such as the investment and operational cost, energy security perspective and the potential environmental and social impacts," of the

six scenarios, all of which included 70 to 85 percent reliance on fossil-fuelled energy, Scenario 2 was adopted for the country's PSMP (Ministry of Energy and Minerals 2016). Dozens of ongoing and planned gas, coal and hydropower plants were calculated in the power expansion plan to reach up to 22,595 MW installed generation capacity by 2040, including 23 large- and medium-scale hydropower projects, 10 gas power developments and five coal plants. As of 2016, the total installed capacity in Tanzania was about 1,457 MW (Central Intelligence Agency 2020). According to the PSMP, Scenario 2 has an overall cumulative cost of about 57.46 million USD and includes 75 percent of the energy generation mix derived from gas and coal plants *(Table 3-2)*.

Table 3-2: Proposed Energy Mixes

Scenario	Gas	Coal	Hydro	Renewables and others*	Cost** (in million USD)
1	50%	25%	20%	5%	58,664
2	40%	35%	20%	5%	57,462
3	35%	40%	20%	5%	57,098
4	25%	50%	20%	5%	56,368
5	50%	35%	10%	5%	58,576
6	40%	30%	20%	10%	72,049

Scenario 2	Gas	Coal	Hydro	Renewables and others*	Total Installed Generation Capacity
By 2040	10,253 MW	6,000 MW	5,093 MW	1,250 MW	22,595 MW

**Renewables and others include solar, wind, biomass, geothermal and imported power.*
***Cost is the estimated cumulative value of the following from 2015 to 2040:*
Investment Cost – Salvage Value + Fuel Cost + Operation & Maintenance Cost

Source: Ministry of Energy and Minerals 2016

3.2.1 Emissions Increase

The adopted scenario conflicts with efforts to provide a sustainable solution that is environmentally conscious. With a plan that relies heavily on high-emission energy sources, the implications on the health of the people and the environment are costly. Based

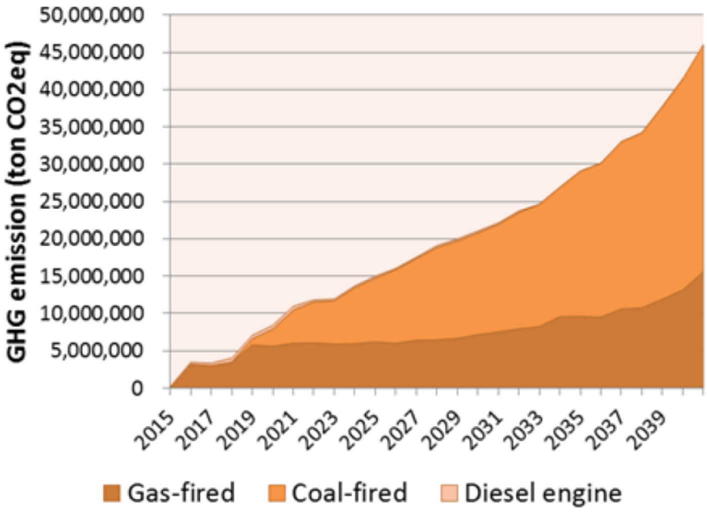


Figure 3-2: Estimated CO2 Emissions of Scenario 2 (Ministry of Energy and Minerals 2016)

on Scenario 2, the PSMP notes that CO_2 emissions will increase 13.5 times from 2015 to 46 million tons in 2040 *(Figure 3-2)*. CO_2, a byproduct of power generated by coal, is regarded as a principal GHG contributing to climate change.

Similarly, nitrogen oxide (NOx) emissions are estimated to increase 12.5 times to 78,600 tons *(Table 3-3)*, and from 2020, sulphur oxide (SOx) emissions are projected to increase 6.8 times to 256,900 tons (Ministry of Energy and Minerals 2016). The authors of the PSMP concede that air pollution, calculated from the projected annual fuel consumption, is harmful to human and environmental health and could consequently affect the agriculture industry, which employs about 67 percent of Tanzania's labor force. *"Pollutants like SOx and NOx contribute to the incidence of acid rain or acidification. It could cause impacts on freshwater aquatic ecosystems, vegetation and drinking water. The acidification of soils can also have an adverse impact on agricultural productivity"* (Ministry of Energy and Minerals 2016).

Table 3-3: Projected Emissions from Scenario 2

Emission	2015	2040
Carbon Dioxide – CO_2	3.4 million tons	46 million tons
Nitrogen Oxide – NOx	6,300 tons	78,600 tons
Sulphur Oxide – SOx	0 (37,800 tons in 2020)	256,900 tons

Source: Ministry of Energy and Minerals 2016

The adopted scenario would achieve the goal – to provide access to electricity to all – but it could also prove prohibitive toward socio-economical development. To help address the SDGs of the 2030 Agenda, as well as the Paris Agreement on climate change, Tanzania should consider alternatives to coal and gas power and adopt low-emission energy sources, such as nuclear and other renewable energies.

3.3 Small Modular Reactor Deployment Potential

The PSMP reported on each of the 30 official regions of Tanzania[1] – 25 mainland regions plus five offshore regions of Zanzibar. The scope of this case study focuses on the mainland regions, in which the following regions are grouped, based on data presented in the PSMP:

- Iringa + Njombe
- Mwanza + Geita
- Rukwa + Katavi

[1] *On 29 January 2016, an additional region – Songwe – was established out of the Mbeya region* (President's Office Regional Administration and Local Government 2020). *For the purpose of this study, Mbeya is evaluated inclusive of Songwe.*

- Shinyanga + Simiyu

To demonstrate the potential of SMRs and MMRs, regional electrification rate and regional peak demand form the basis of evaluation in which SMRs and MMRs would be applicable. Regional electrification rate is vital to address regional demands comprising residential and industrial consumption. Peak demand refers to the highest load drawn from the grid.

Figure 3-3 illustrates the different regions of Tanzania. The 2015 recorded rates of electrification and peak demand are listed with 2030 projections, respectively.

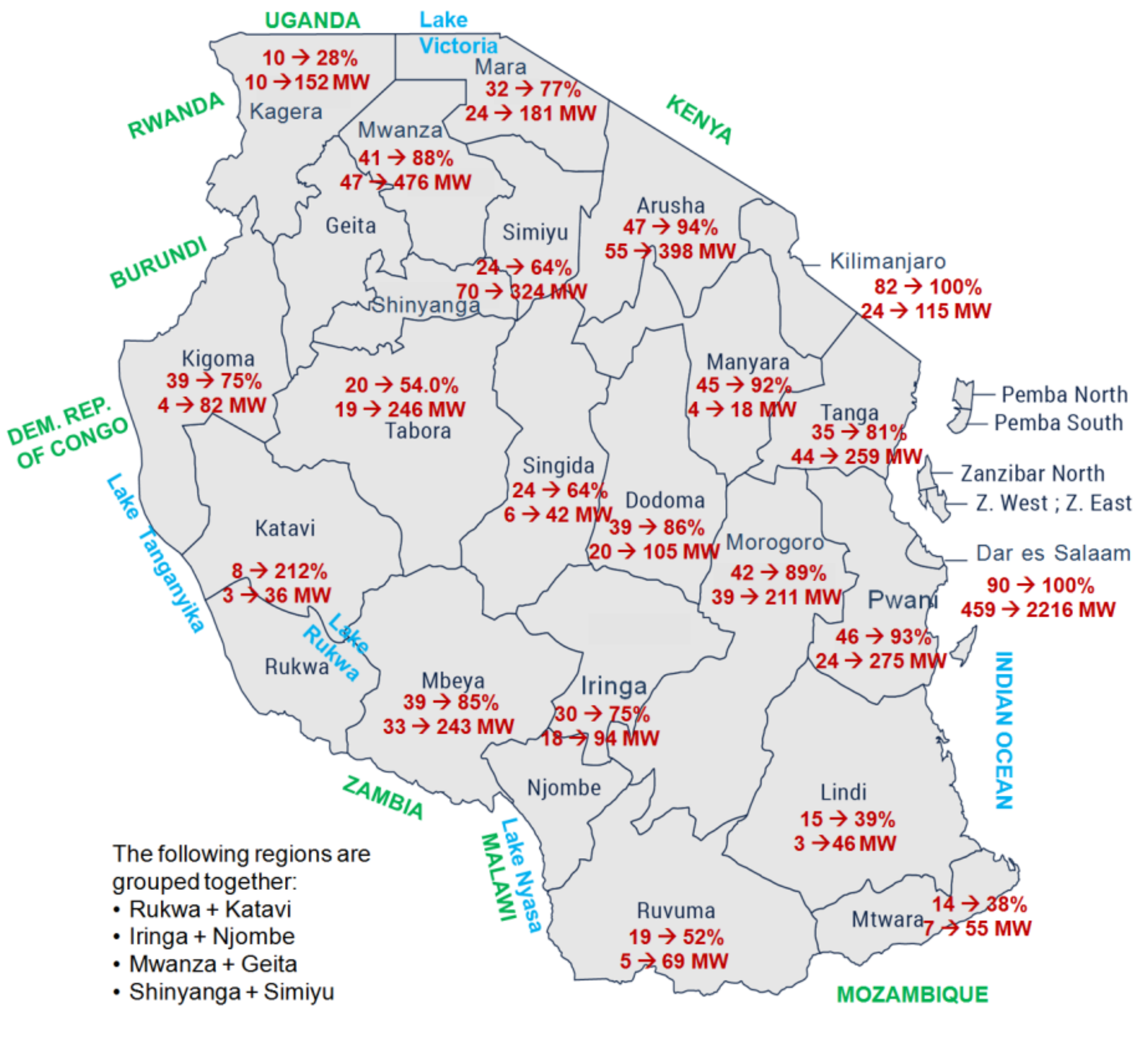


Figure 3-3: 2015 to 2030 Projections of Mainland Tanzania
2015 → 2030 Projection of Regional Electrification Rate (%)
2015 → 2030 Projection of Regional Peak Demand (MW)
Source: Ministry of Energy and Minerals 2016

In 2015, Tanzania recorded an electrification rate of about 35 percent and a peak demand of 918 MW on the mainland (*Table 3-4)*. Tanzania plans to incrementally reach just over 70 percent electrification rate on the mainland with peak demand forecast at 5,643 MW by 2030 and 100 percent electrification rate with a peak demand of about 14,000 MW by 2040. Fossil-fuelled thermal and hydro power plant projects are proposed to meet the projected demand, along with the expansion of transmission system lines.

Table 3-4: Regional Rates of Electrification and Peak Demand

	Regional Electrification Rate (%)				Regional Peak Demand (MW)			
Region	**2015**	**2025**	**2030**	**2035**	**2015**	**2025**	**2030**	**2035**
Arusha	47.2	88.6	94.1	100	55	256	398	613
Dar es Salaam	89.8	100	100	100	459	1,407	2,216	3,416
Dodoma	39.4	74	86	100	20	65	105	169
Iringa + Njombe	30	56.4	75.1	100	18	55	94	159
Kagera	10.4	19.6	27.7	39.2	10	92	152	254
Kigoma	29.6	55.6	74.6	100	4	48	82	138
Kilimanjaro	82.1	100	100	100	24	77	115	173
Lindi	14.5	27.2	38.5	54.4	3	27	46	77
Manyara	45.4	85.2	92.3	100	4	13	18	25
Mara	31.5	59.2	76.9	100	24	107	181	307
Mbeya	38.6	72.4	85.1	100	33	151	243	390
Morogoro	42.2	79.2	89	100	39	133	211	328
Mtwara	14.3	26.8	37.9	53.6	7	32	55	95
Mwanza + Geita	41.2	77.4	88	100	47	290	476	774
Pwani	45.8	86	92.7	100	24	173	275	442
Rukwa + Katavi	8.1	15.2	21.5	30.4	3	21	36	61
Ruvuma	19.4	36.4	51.5	72.8	5	39	69	122
Shinyanga + Simiyu	24.1	45.2	63.9	90.4	70	185	324	571
Singida	24.1	45.2	63.9	90.4	6	23	42	74
Tabora	20.3	38.2	54	76.4	19	133	246	451
Tanga	35	65.8	81.1	100	44	159	259	422
Average	**34.9**	**59.7**	**71.1**	**86.1**				
				Total	**918**	**3,486**	**5,643**	**9,061**

Source: Ministry of Energy and Minerals 2016

Table 3-5: Tanzania's Transmission System

Length	Voltage
647 km	400 kV
2,745 km	220 kV
1,626 km	132 kV
580 km	66 kV

Source: Ministry of Energy and Minerals 2016

Distribution lines of different ranges of voltage capacities comprise Tanzania's transmission system *(Table 3-5)*. TANESCO imports power from Uganda via 132 kV and from Zambia via 66 kV lines (Ministry of Energy and Minerals 2016, 66). TANESCO is securing transmission capacity domestically and with neighbouring countries, including Uganda, Zambia, Kenya and Mozambique. The PSMP's generation and transmission plan to 2030 informs potential locations for SMR and MMR installation. Based on regional peak demand, the PSMP's proposed generation projects and transmission plans by 2030, Tanzania has SMR deployment potential of approximately 4,750 MW by 2030 and beyond.

SMR plant	Capacity in MW	Number of Units	Regions Covered
1 – near Lake Rukwa	625	2 - 3	• Rukwa + Katavi • Kigoma • Tabora • Mbeya • Iringa + Njombe
2 – near Lake Victoria	1,025	3 - 4	• Mwanza + Geita • Shinyanga + Simiyu • Kagera • Singida • Mara
3 – near Tanga	750	2 - 3	• Tanga • Kilimanjaro • Manyara • Arusha • Dodoma
4 – near Dar es Salaam	2,050	6 - 7	• Dar es Salaam • Pwani • Morogoro
5 – near Lindi	300	1	• Mtwara • Ruvuma • Lindi • Pwani
Total	4,750	14 - 18	

Table 3-6: Proposed Small Modular Reactor Deployment in Tanzania by 2030

Five potential locations are identified for the deployment of SMRs to replace approximately 4,750 MW of existing or proposed fossil-fuelled sources of energy by 2030 *(Table 3-6 and Figure 3-4)*. Potential sites were selected with consideration of regional peak demand and proximity to water sources for cooling, if necessary.

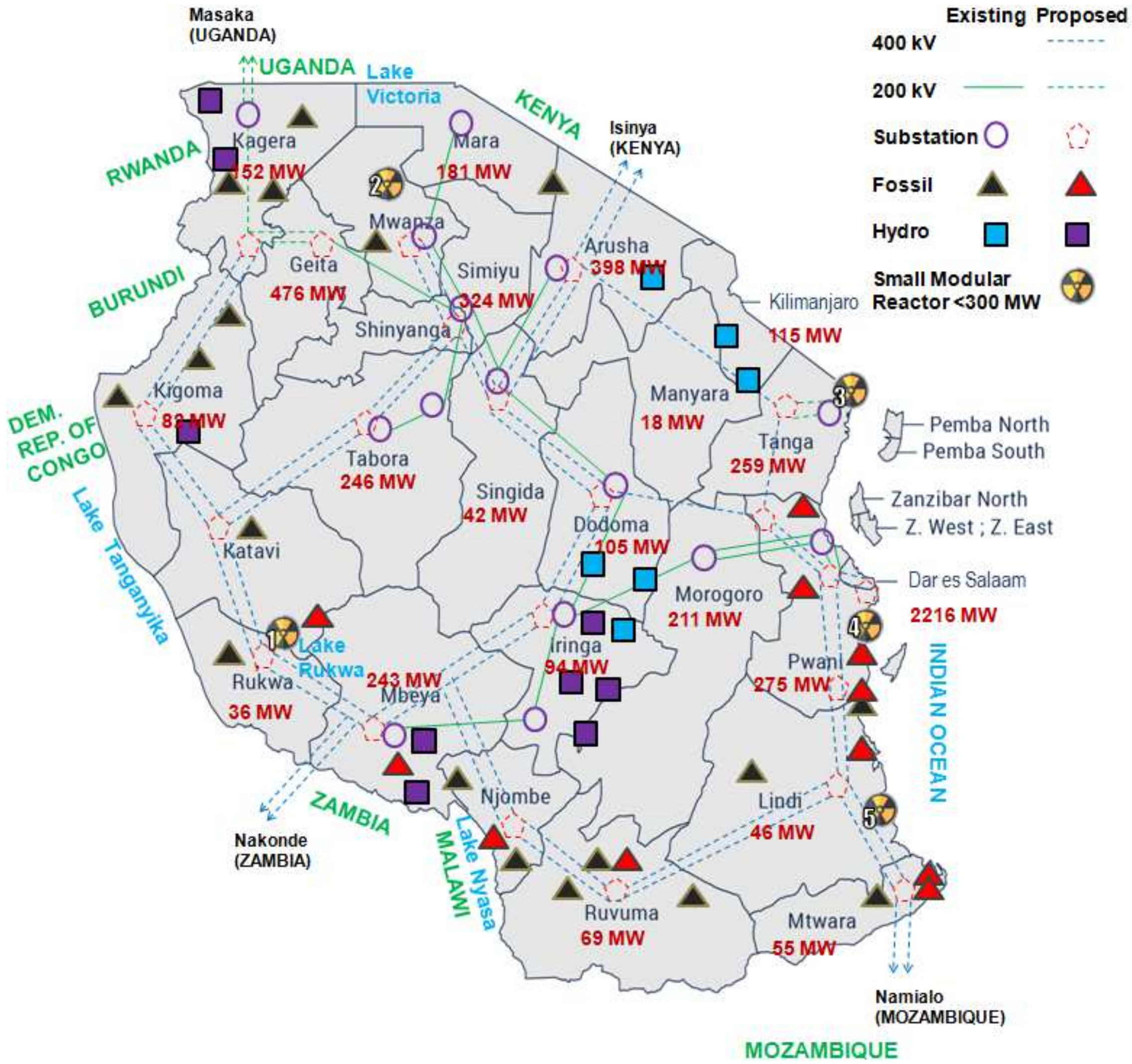


Figure 3-4: Proposed Small Modular Reactors Deployment in Tanzania by 2030 Based on Regional Peak Demand (MW) and Generation & Transmission Plan

3.4 Mini-Grids and Micro Modular Reactor Deployment Potential

Reaching rural areas is one of the greater challenges to achieving universal access to energy. MMRs could be part of the solution in areas lacking sufficient lines of transmission and grid capacity. If Tanzania is unable to reach generation and transmission plan projections by 2030 and beyond, MMR deployment, in conjunction with mini-grids, could play a notable role in rural electrification to reach the government's goal of about 75 percent electrification rate by 2030.

The World Resources Institute defines mini-grids as *"electrical generation and distribution systems of less than 10 MW"* and asserts that they will be key to accelerating energy access in sub-Saharan Africa (Odarno, et al. 2017, 5). Mini-grids provide electricity in rural areas, where the chances of being connected to the national grid are low. *"Electricity from mini-grids can serve an estimated 140 million rural*

Africans by 2040 if 100,000 to 200,000 mini-grids are built," according to the World Resources Institute. As of 2015, Tanzania had at least 109 mini-grids in 21 regions with an installed capacity of 157.75 MW, serving about 184,000 customers (Odarno, et al. 2017). About 85 percent of Tanzania's mini-grids operate in isolation outside of the national grid *(Table 3-7)*.

Table 3-7: Mini-Grids in Tanzania by Energy Source

Energy Source	Mini-Grid Plants	Connected to Grid	Isolated from Grid	Installed Capacity (kW)	Number of Customer Connections
Hydro	49	9	40	32,921	11,925
Biomass	25	7	18	51,714	562
Solar	13	0	13	234	1,153
Fossil Fuels	19	0	19	72,700	170,065
Hybrid	3	0	3	177	**
All sources	**109**	**16**	**93**	**157,748**	**183,705**

Source: Odarno, et al. 2017

About 46 percent of mini-grid capacity is met with fossil fuels; however, there are associated challenges with the high-emission energy source. While fuel and equipment are available in urban areas, they are not as available or accessible in rural areas. Maintenance is also a challenge in rural areas and results in an unreliable power supply. Moreover, fossil-fuelled mini-grid plants tend to have minimal lifespans between 10 to 15 years, compared with mini-grids based on renewable technologies, such as hydro with 40 to 100 years (Odarno, et al. 2017).

Renewable energy sources – hydro, biomass and solar – account for 54 percent of installed capacity and provide electricity for about 7 percent of mini-grid connections. *"Renewable energy mini-grids can accelerate electrification in remote rural communities, particularly in areas with limited access to consistent fuel supply and spare parts needed to maintain fossil fuel technologies"*(Odarno, et al. 2017, 26). MMRs present another clean-energy option that could supplement renewable energy sources, which are also subject to climate variability.

Based on the location of mini-grids in 2016, proposed transmission lines and proposed fossil-fuelled power plants identified in the PSMP, 39 potential locations are identified for the deployment of MMRs to replace fossil-fuelled sources of energy and to supplement renewable energy sources to meet projected regional demands in 2030 *(Figure 3-5)*. Contrary to SMRs, MMRs do not require a body of water or cooling tower, and minimal site preparation is required.

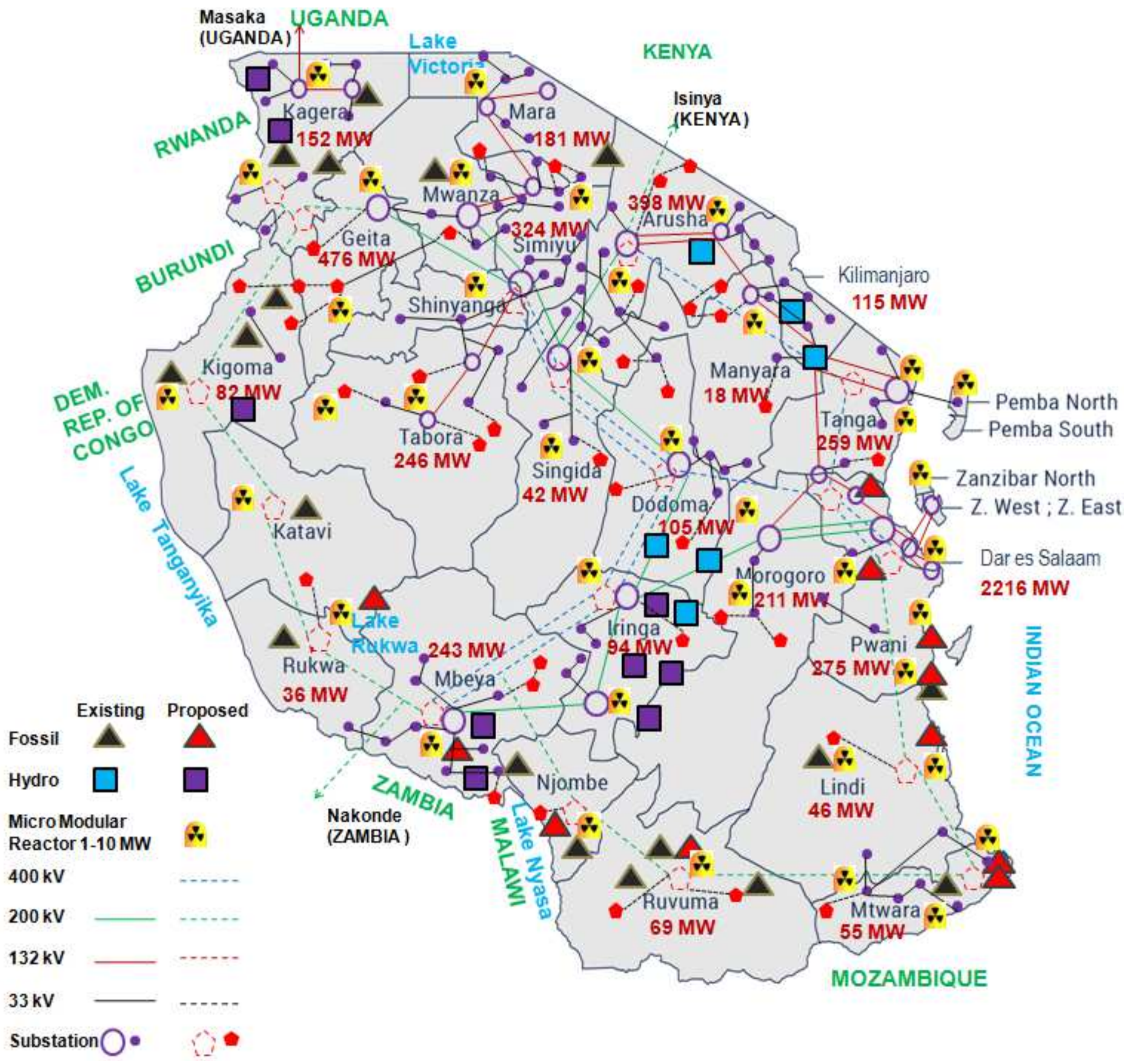


Figure 3-5: Proposed Micro Modular Reactor Deployment in Tanzania by 2030 Based on Regional Peak Demand (MW) and Location of Mini-Grids

3.5 Carbon savings

One of the main drivers behind SMR and MMR consideration is the amount – or lack thereof – of emissions that are emitted from energy production. Essentially, the carbon footprint associated with the deployment of SMR and MMR is minimal in comparison with coal and gas options. In Scenario 2 of Tanzania's PSMP, coal and gas power plants comprise about 75 percent of the country's energy mix by 2040, resulting in 46 million tons of CO_2 emissions.

If the proposed five SMR plants were to be implemented, contributing to approximately 4,750 MW power generation, then 84 percent of the country's mainland

2030 peak demand could be supplied with zero-emission generation. The proposed SMR plants would lead to a significant drop in emissions from power generation in 2030 – potentially eliminating more than 18 million tons of CO_2 emissions – which would have further long-term implications in the years to follow. *Table 3-8* provides the estimated incremental increase in emissions linked to thermal – coal and gas – power expansion based on the PSMP and the estimated emissions if the proposed SMR plants were to be implemented.

Table 3-8: Estimated Emissions from Scenario 2

	Estimated Emissions in Tons			**Estimated Emissions in Tons with SMRs**		
	CO_2	**NOx**	**SOx**	**CO_2**	**NOx**	**SOx**
2015	3,400,000	6,300				
2020	11,000,000	22,500	37,800			
2025	16,500,000	30,000	86,000			
2030	22,000,000	40,500	124,000	3,520,000	6,480	19,840
			Potential savings	18,480,000	34,020	104,160

Further emissions savings could be realized with the implementation of MMRs to replace existing and proposed thermal power plants. Oklo claims that its 1.5-MW MMR, which is designed to operate for up to 20 years before refuelling, could *"save 1,000,000 tons of carbon emissions during its operation over diesel generator alternatives at remote sites"* (Chan 2020).

3.6 International Legal Instruments

While the scale of SMRs and MMRs is significantly smaller, adherence to all international legal instruments must be planned (Chitumbo 2019). Newcomer countries, such as Tanzania, should consider the time and resources to establish the legal instruments to coincide with and not delay the progress of potential SMR or MMR deployment. Since 1976, Tanzania has been a member of the IAEA and has become a party to some of the necessary legal instruments, namely:

- Convention on the Physical Protection of Nuclear Material
- Convention on Early Notification of a Nuclear Accident
- Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency
- Revised Supplementary Agreements Concerning the Provision of Technical Assistance by the IAEA

- African Regional Co-operative Agreement for Research, Development and Training Related to Nuclear Science and Technology
- Agreement between the United Republic of Tanzania and the IAEA for the Application of Safeguards in connection with the NPT
- Additional Protocol to the Agreement between the United Republic of Tanzania and the IAEA for the Application of Safeguards in connection with the NPT (IAEA Office of Legal Affairs 2019).

As Tanzania continues to expand its nuclear uses, so shall its legal framework. Following the IAEA's guidance to nuclear law and the proposed roadmaps to deployment, the country will need to become a party to:

- Convention on Nuclear Safety
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management
- Vienna Convention on Civil Liability for Nuclear Damage
- Convention on Supplementary Compensation for Nuclear Damage
- Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention.

3.7 Summary of Case Study Results

The comprehensive PSMP provided a basis to conduct the case study. Based on Tanzania's goals to increase energy access and to meet projected demand, the country's energy portfolio will expand dramatically in the next decades. Alongside renewable energy options, there is an opportunity to pursue nuclear power to provide a sustainable, reliable and clean solution, which could lead to a significant impact in reducing emissions produced from the energy sector. The case study demonstrates the potential for SMR and MMR deployment in Tanzania based on projected regional peak demand and generation and transmission plans.

The five SMR plants' deployment, accounting for approximately 4,750 MWe or 84 percent of the country's peak demand in 2030, could theoretically save more than 18 million tons of CO2 emissions. Given the prevalence of mini-grids, 39 MMRs providing up to 390 MW total capacity are proposed throughout the country to replace fossil-fuelled sources of energy and to supplement renewable energy sources to meet projected regional demands in 2030. Both of the SMR and MMR deployment proposals illustrate how modular reactors could play a major role in meeting peak demand in the

25 mainland regions of the country. The study provides an example of how SMR and MMR deployment could be considered for a number of interested nuclear newcomer countries. Additionally, the result of the study establishes a starting point to investigate the feasibility of deployment. The identified sites of modular reactors would require a comprehensive feasibility study that would consider, but not be limited to:

- Safety
- Licensing
- Public Acceptance
- Financial feasibility
- Economics of SMR investment and production
- Scalability – factory production and capital cost
- Environmental impact assessment

4. Conclusion

SMRs and MMRs could play a vital role in reducing GHG emissions and climate change mitigation. This nuclear option presents potential and advantages in providing access to sustainable, affordable and reliable energy – SDG 7 – particularly for countries with limited grid capacity and with higher demand in rural or isolated areas. Given the limited capacity and varied sources of energy that comprise countries' portfolios, there is potential for SMRs and MMRs to complement the expansion of renewable energy sources, as well as power sector decarbonisation. For utilities in remote areas where large-scale plants cannot be physically or economically connected to a power grid, the range of power plant sizes is significantly smaller. Furthermore, SDG 7 aims to *"expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries"* by 2030 (United Nations 2018).

The scale of SMRs simplifies some infrastructure issues, such as siting – the selection and evaluation of a site for nuclear installation – which would likely influence costs, public acceptance and safety of the installation in a favourable way. Infrastructure developed for SMRs could also support future endeavours for a large-scale nuclear power programme.

The roadmap presented in this paper could serve as a model to deploy modular reactors to address and overcome challenges faced by emerging nuclear newcomer countries as they expand their energy portfolios. While the time from initial consideration of nuclear power plants to launching operations is about 10 to 15 years, the time for SMR and MMR deployment could range from 7 to 10 years and from 4 to 7 years, respectively. Much of the timing and activities related to the roadmap is contingent on the selected technology. The roadmap can be further adapted to country-specific needs and should be adapted to the selected technology.

The existing legal framework applied to the peaceful uses of nuclear technology and today's nuclear power plants sets the precedence for the legal framework necessary to deploy SMRs and MMRs. The proposed roadmaps and guidance to nuclear law alludes to 12 relevant international legal instruments, of which few agreements, such as the NPT and Convention on the Physical Protection of Nuclear Material, have already been adopted by many countries.

One of the main obstacles to the deployment of SMR and MMRs is that the technology is not yet proven for commercial utilization. There is an inherent factor of unknowns and uncertainties that will have to be addressed in due time.

4.1 Recommendations

1. The 3SBD concept should be further explored in the design and technical development of SMR and MMR technology. There is a timely opportunity to address concerns and unite the efforts of regulators, operators, vendors and consumers. It is evident that the international community and nuclear industry recognize the potential and impending deployment of SMR technology. Knowing that effective and efficient preparation is paramount to the first successful deployments of SMRs and MMRs, there should be a sense of urgency to prepare and establish guidance and initial standards to get ahead of the curve.
2. A thorough technology evaluation should be conducted to understand the sustainability, safety, economics, adaptability to environments, etc., of the various SMR designs under development. Some designs will be realized, while others may not progress beyond a concept design. With more than 50 designs in various stages – from concept design to construction – there is a need to evaluate the reality and feasibility of these potential technologies.
3. The thesis mainly focused on the regulatory framework from the limited perspective of SMR deployment. The regulatory framework should be further evaluated to consider the operation of SMRs. Given that units and plants could be physically distributed across various areas, the regulatory framework may need to be adjusted accordingly. Likewise, the licensing processes should also be evaluated in consideration of the distribution factor.
4. There are industry-wide initiatives to support women in the nuclear field, and the developing field of SMR development and deployment should further those efforts. Given the number of emerging nuclear newcomers, compounded with the expanding field of SMRs, there should be a concerted effort to promote diversity and inclusion.

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Annex: Roadmap Analysis

Milestone 1: Ready to make a knowledgeable commitment to a nuclear power programme

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
M1-1. National Position		
1.1. Nuclear power option included in national energy strategy	Yes	Yes
1.2. Nuclear Energy Programme Implementing Organization (NEPIO) established and staffed	Yes	Yes
Activity_M1-1.1: Develop national energy planning for next 20-30 years **Activity_M1-1.2:** Conduct pre-feasibility study or develop comprehensive report covering 19 nuclear infrastructures **Activity_M1-1.3:** International cooperation – IAEA, WANO, reactor technology suppliers, universities etc.		
M1-2. Nuclear Safety		
2.1. SMR/MMR utilization	• National electricity supply • Mining and heavy industry • Water desalination • District heating • Hydrogen production • Rural /remote electrification • Island electrification	• Rural/remote electrification • Island electrification • Mining and heavy industry • Water desalination • District heating • Hydrogen production
2.2. Unit size (MWe)	10 – 300	<10
2.3. Typical plant output (MWe)	100 – 600	4 – 100
2.4. Plant life (years)	60	10-30
2.5. Core damage frequency		
Activity_M1-2.1: Conduct SMR technology assessment **Activity_M1-2.2:** Join Convention on Nuclear Safety and cooperate with international organizations on nuclear safety		
M1-3. Management		
3.1. Identify future organizations & responsibilities ➢ Regulatory organization ➢ Owner / operator organization ➢ Education & training institutes ➢ Technical support organization	Yes	Yes
3.2. Evidence on appropriate expertise and experience involved	Yes	Yes
3.3. Identify reactor technology suppliers	Yes	Yes

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
Activity_M1-3.1: Report on future organization, roles and responsibilities, and organization structure **Activity_M1-3.2:** Identify external consultants and advisers with appropriate experience: prepare and review documents **Activity_M1-3.3:** Identify potential reactor technology suppliers and cooperation arrangements		
M1-4. Funding and Financing		
4.1. Reactor Cost (Billion USD) – Unit Size Range	0.06 – 2.0	0.02 – 0.15
4.2. Overnight Cost (USD/kWe) • First of a Kind (FOAK) • Nth of a Kind (NOAK)	4,000 to 5,000	4,000
4.3. Levelized Cost of Electricity • First of a Kind (FOAK) • Nth of a Kind (NOAK)	• 65/MWh • 58.5/MWh	• 0.14-0.41/kWh • 0.09-0.33/kW
4.4. Adequate Funding for NEPIO Provided	Yes	Yes
Activity_M1-4.1: Analysis of cost of different SMR/MMR technologies available in the market **Activity_M1-4.2:** Develop report on strategies for funding and financing for 1) establishing organizations, 2) building nuclear infrastructure and 3) performing activities across all phases of nuclear power programme		
M1-5. Legal Framework		
5.1. Adherence to all relevant international legal instruments planned	Yes	Yes
5.2. Plans for national nuclear legislation to be enacted	Yes	Yes
Activity_M1-5.1: Develop a plan approved by the government to adhere to all relevant international legal instruments with timelines **Activity_M1-5.2:** Develop a plan approved by the government for completion of national nuclear legislation		
M1-6. Safeguards		
6.1. Obligations under NPT and non-proliferation treaties and other international instruments, recognized	Yes	Yes
6.2. Development, implementation and enforcement of safeguards framework, including SSAC establishment, planned	Yes	Yes
Activity_M1-6.1: Develop a plan approved by the government to adhere to NPT and Comprehensive Safeguards Agreement		
M1-7. Regulatory Framework		
7.1. Development of an adequate regulatory framework planned	Yes	Yes
7.2. Establish regulatory body, its organizational structure, roles and responsibilities, funding etc.	Yes	Yes
Activity_M1-7.1: Develop a plan approved by the government covering all aspects of regulatory framework		
M1-8. Radiation Protection		
8.1. Hazards presented by nuclear	Yes	Yes

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
power plant operation recognized		
8.2. Enhancement to national regulations and infrastructures planned	Yes	Yes
Activity_M1-8.1: Develop a plan to implement radiation protection programme across the lifecycle of nuclear power plant		
M1-9. Electrical Grid		
9.3. Existing national electrical grid capacity (MWe)	300 – 4000	40 – 300
9.4. Electrical grid status for electricity supply	• On-grid • Isolated grid • Off-grid	• Isolated grid • Off-grid
Activity_M1-9.1: Develop National Electricity System Planning		
M1-10. Human Resource Development		
10.1. Manpower required for operation	60 - 375	15 - 50
10.2. Necessary knowledge and skills identified	Yes	Yes
10.3. Develop and maintenance of human resource base planned	Yes	Yes
Activity_M1-10.1: Develop a human resource development plan for future organizations with organization structure, roles and responsibilities, manpower required, recruitment, training and managing human resource across each phase		
M1-11. Stakeholder Involvement		
11.1. Strong public information and education programme initiated	Yes	Yes
11.2. Need for open and timely interaction and communication regarding the nuclear power programme addressed	Yes	Yes
Activity_M1-12.1: Develop a public communication and stakeholder engagement plan		
M1-12. Site and Supporting Facilities		
12.1. Plant footprint (Acres)	13 - 74	0.1 - 5
12.2. Heat sink	• Sea/river/deep lake • Cooling towers (dry cooling)	• Cooling towers (dry cooling) • Lake • Not Required
Activity_M1-12.1: Conduct site survey and selection of potential sites		
M1-13. Environmental Protection		
13.1. Unique environmental issues recognized	Yes	Yes
13.2. Environmental impact assessment production and communication recognized	Yes	Yes
13.3. An effective environmental framework for existing uses of radiation sources in place	Yes	Yes
Activity_M1-13.1: Develop a plan for environmental issues related to use of nuclear energy		
M1-14. Emergency Planning		
14.1. Exclusion zone	Site Boundary	Site Boundary

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
14.2. Appreciation of the need for emergency planning, developed	Yes	Yes
14.3. Communication with and involvement of local and national government taken into account	Yes	Yes
14.4. Emergency planning for existing radiation facilities and practices	Yes	Yes
Activity_M1-14.1: Develop a plan for environmental issues		
M1-15. Nuclear Security		
15.1. Requirements for security and physical protection acknowledged	Yes	Yes
15.2. Necessary regulation identified	Yes	Yes
15.3. Effective security protection for existing uses of radiation sources	Yes	Yes
Activity_M1-15.1: Develop a plan for nuclear security – policy, roles, structure, responsibilities and reporting requirements **Activity_M1-15.2:** Plan to develop national legislation providing a basis for regulation of security and physical protection arrangements regarding nuclear facilities, nuclear and other radioactive material, its transportation and storage, including provisions for licensing, inspection and sanctions		
M1-16. Nuclear Fuel Cycle		
16.1. Fuel cycle (months)	24 - 48	120 - 360
16.2. Knowledge of nuclear fuel cycle steps and approaches developed	Yes	Not Required
16.3. Need for site spent fuel storage recognized	Yes	Not Required
16.4. Interim spent fuel storage considered	Yes	Not Required
Activity_M1-16.1: Develop a document on national fuel cycle strategy and address non-proliferation issues, regulatory requirements **Activity_M1-16.2:** Develop a document on importance of adequate capacity for on-site spent fuel storage, taking into account fuel cycle options		
M1-17. Radioactive Waste Management		
17.1. Radioactive waste management	• On-Site Storage • Off-Site Facility	Off-Site Facility
17.2. Burdens of radioactive waste recognized	Yes	Yes
17.3. Review capabilities for waste processing, storage and disposal	Yes	Not Required
17.4. Options for ultimate disposal of high-level radioactive waste	Yes	Not Required
Activity_M1-17.1: Develop a document on significant implications of radioactive waste, need for national capabilities, regulatory framework, financing scheme and infrastructure for radioactive waste management.		
M1-18. Industrial Involvement		
18.1. Role of industrial involvement	Prominent Role	Not Required *(Unless vendor plans to*
18.2. National policy with respect to	Yes	

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
national and local industrial involvement considered		*manufacture MMR in the newcomer country itself)*
18.3. Need for strict application of quality programmes for nuclear equipment and services recognized	Yes	
Activity_M1-18.1: Develop a strategy for industrial involvement with localization percentage it could achieve, importance of highly regulated quality programmes in nuclear industry		
M1-19. Procurement		
19.1. Unique requirements associated with purchasing nuclear equipment and services recognized	Yes	Yes
19.2. Consistent policies for nuclear procurement in place	Yes	Yes
Activity_M1-19.1: Develop a Strategy for Procurement and Operation of NPPs and its associated Financing plan		

Milestone 2: Ready to invite bids for the first SMR/MMR

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
M2-1. National Position		
1.1. Government support evident	Yes	Yes
1.2. Commitments and obligations of owner/operator organizations established	Yes	Yes
Activity_M2-1.1: Conduct feasibility study for first SMR/MMR		
M2-2. Nuclear Safety		
2.1. Safety responsibilities by all stakeholders recognized	Yes	Yes
2.2. Safety culture evaluated	Yes	Yes
2.3. Long-term relationship with supplier established	Yes	Yes
Activity_M2-2.1: Develop safety culture and safety programme for owner/operator organization		
M2-3. Management		
3.1. Bid invitation specification (BIS) available	Yes	Yes
3.2. Adequate staff available to prepare for and analyse bids	Yes	Yes
3.3. Bid evaluation criteria determined	Yes	Yes
3.4. Contracting strategy established	Yes	Yes
3.5. Project management organization established	Yes	Yes
3.6. Management systems established	Yes	Yes
Activity_M2-3.1: Develop bid invitation specification (BIS), bid evaluation criteria and contracting strategy **Activity_M2-3.1:** Establish project management organization		
M2-4. Funding and Financing		
4.1. Strategy for management of financial risks available	Yes	Yes
4.2. Funding and financing plan available	Yes	Yes
Activity_M2-4.1: Ensure adequate funding and financing available, and risk management plan identifying key financial risks		

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
M2-5. Legal Framework		
5.1. International legal Instruments governing nuclear activities in force	Yes	Yes
5.2. A comprehensive nuclear law is enacted and in force	Yes	Yes
5.3. Legislation dealing with the nuclear power programme developed, promulgated and in force	Yes	Yes
Activity_M2-5.1: National nuclear law is in place, adopted international legal instruments and other laws relevant to nuclear power programme		
M2-6. Safeguards		
6.1. Terms of international safeguards agreement in place	Yes	Yes
6.2. State system of accounting for and control of nuclear material (SSAC) established and operational	Yes	Yes
6.3. Early safeguards relevant information provided to IAEA	Yes	Yes
6.4. Specific legislation and relevant safeguards procedures in place	Yes	Yes
Activity_M2-6.1: Establish SSAC with relevant roles and responsibilities and technical competence **Activity_M2-6.2:** Sign or become member to Comprehensive Safeguard Agreement and other Agreements with IAEA		
M2-7. Regulatory Framework		
7.1. Independent nuclear regulatory body established	Yes	Yes
Activity_M2-7.1: Establish independent regulatory body with organization structure, roles and responsibilities, staffing and training requirements **Activity_M2-7.2:** Develop relevant codes and standards required for Phase 2 and later for Phase 3 and beyond		
M2-8. Radiation Protection		
8.1. Actions to prepare adequate radiation protection programs undertaken	Yes	Yes
8.2. Expansion of appropriate infrastructures planned	Yes	Yes
Activity_M2-8.1: Ensure radiation monitoring and protection programme, environment monitoring programme in place **Activity_M2-8.2:** Evidence of radiation protection team expansion for regulatory board and owner/operator organization with necessary funds, recruitment and training		
M2-9. Electrical Grid		
9.1. Detailed studies to determine grid expansion, upgrade or improvement undertaken	Yes	Not Required
9.2. Plans, funding and schedule for grid enhancement available	Yes	
Activity_M2-9.1: Conduct national electrical grid assessment for SMR/MMR deployment		
M2-10. Human Resource Development		
10.1. Knowledge and skills needed in organizations for Phase 3 and operational phase identified	Yes	Yes
10.2. Plan to develop and maintain the human	Yes	Yes

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
resource base in organizations for Phase 3 and operational phase is developed		
Activity_M2-10.1: Implement human resource development plan for Phase-2: Regulatory body and owner/operator organization **Activity_M2-10.2:** Ensure funds are allotted and relevant infrastructures are in place for human resource development in Phase 3		
M2-11. Stakeholder Involvement		
11.1. Public information and education programme developed	Yes	Yes
Activity_M2-12.1: Develop public communication tools and materials, training of staff/spokesperson in delivering clear messages to public, local government, industry, media, NGOs, opposition groups and neighboring countries		
M2-12. Site and Supporting Facilities		
12.1. Detailed site characterization completed	Yes	Yes
12.2. Site ready for construction	Yes	Yes
Activity_M2-12.1: Conduct detailed site characterization studies, including environmental impact assessment of SMR/MMR project		
M2-13. Environmental Protection		
13.1. Environmental studies for selected sites performed	Yes	Yes
13.2. Particular environmental sensitivities included in BIS	Yes	Yes
13.3. Clear and effective regulation of environmental issues established	Yes	Yes
Activity_M2-13.1: Ensure environmental impact assessment of final site for SMR/MMR deployment is completed in accordance with national and international requirements **Activity_M2-13.2:** Develop information related to site specific environmental issues for BIS **Activity_M2-13.2:** Ensure environmental regulatory role established either within nuclear regulator or within existing environment regulator		
M2-14. Emergency Planning		
14.1. Detailed approach to emergency planning being implemented	Yes	Yes
14.2. Emergency planning for existing radiation facilities and practices	Yes	Yes
14.3. Actions from earlier reviews completed	Yes	Yes
Activity_M2-14.1: Ensure basic regulations, roles and responsibilities to all relevant organizations are communicated **Activity_M2-14.2:** Implement the strategy developed for emergency planning **Activity_M2-14.3:** Completion of all actions from any previous audit or review of existing systems against international requirements, such as those in IAEA Safety Standards Series: GS-R-2 and GS-G-2.1		
M2-15. Nuclear Security		
15.1. Legislation promulgated	Yes	Yes
15.2. Design basis threat (DBT) defined	Yes	Yes
15.3. Security requirements defined	Yes	Yes
15.4. Sensitive information defined	Yes	Yes
15.5. Physical protection by trained on-site security staff provided	Yes	Enhanced Security Needed
15.6. Programmes for selection/qualifications of staff with access to facilities	Yes	Yes
15.7. Security culture promulgated	Yes	Yes
Activity_M2-15.1: Arrangements and draft of agreements covering protocols and programmes for		

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
local and national law enforcement assistance **Activity_M2-15.2:** Ensure the design basis threat defined and outline of security requirements **Activity_M2-15.3:** Security requirements and desirable features planned for the site, physical protection by a trained on-site security personnel **Activity_M2-15.4:** Evidence of the promulgation of a security culture		
M2-16. Nuclear Fuel Cycle		
16.1. Fuel cycle strategy decided	Yes	Yes
Activity_M2 -16.1: Evidence that fuel cycle strategy decisions have been made for both front and back ends of the nuclear fuel cycle		
M2-17. Radioactive Waste Management		
17.1. Handling radioactive waste considered	Yes	Not Required
17.2. Implementation plan for high level waste disposal in preparation	Yes	
Activity_M2-17.1: National Waste Management Organization is defined, policy for management of waste and regulatory requirements, management of all types of waste including high level waste. **Activity_M2-17.2:** An integrated plan for bidding and construction of waste facilities consistent with the power plant construction programme		
M2-18. Industrial Involvement		
18.1. Realistic assessment of national and local capabilities carried out	Yes	Not Required *(Unless vendor plans to manufacture MMR in the newcomer country)*
18.2. Ability to meet schedule and quality requirements analyzed	Yes	
18.3. Plans and programmes to transition to national and local suppliers	Yes	
Activity_M2-18.1: Extent of national industrial participation agreed and established and desired targets for local and national industrial involvement included in the BIS **Activity_M2-18.2:** Develop list of approved vendor/supplier and their qualification, including quality control and assurance requirements **Activity_M2-18.3:** Support national industries with technology advancement requirements, training and improvement in quality standards to qualification as an approved vendor/supplier		
M2-19. Procurement		
19.1. Owner/operator competence to carry out nuclear procurement evident	Yes	Yes
19.2. Procurement programme consistent with national policy for industrial participation established	Yes	Yes
Activity_M2-19.1: Evidence of a qualified and experienced procurement team **Activity_M2-19.2:** A procurement programme described in the bid/BIS that delineates the scope of supply for specific equipment and services. **Activity_M2-19.3:** Develop a detailed project schedule for construction/installation, Commissioning and operation of first SMR/MMR project		

Milestone 3: Ready to commission and operate the first SMR/MMR

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
M3-1. National Position		
1.1. Government role assigned and effective	Yes	Yes
1.2. National Strategy Successfully Implemented	Yes	Yes
1.3. Long term support through international	Yes	Yes

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
cooperation evident		
Activity_M3-1.1: Ensure Govt. coordination is still in place across organizations (Owner/Operator Organization, Regulatory Body, Training Institutes and Universities) for development of infrastructures to achieve Milestone 3		
M3-2. Nuclear Safety		
2.1. Basis of safety understood	Yes	Yes
2.2. Leadership and safety culture evident	Yes	Yes
2.3. Action plan in place to address any licensing issues	Yes	Yes
2.4. Operating organization design integrity process defined and effective	Yes	Yes
Activity_M3-2.1: Establish safety culture across operating organization **Activity_M3-2.2:** Develop action plan to address any licensing issues, construction and procurement issues etc.		
M3-3. Management		
3.1. Ongoing arrangements for support clear	Yes	Yes
3.2. Structure and staffing of the Operating Organization are adequate for commissioning and operation	Yes	Yes
3.3. Management system for operation developed	Yes	Yes
3.4. Mechanisms for verification of construction and for handover of systems, structures and components from main supplier in place	Yes	Yes
Activity_M3-5.1: Ensure staffing of operating organization are adequate to achieve Milestone 3 **Activity_M3-5.2:** Management team shall ensure construction/installation of SMR/MMR is on schedule and identify any delays in advance, its risks and capabilities/infrastructure required to tackle those issues **Activity_M3-5.3:** Conduct training programme to operating organization staff, and qualify licensed reactor operator		
M3-4. Funding and Financing		
4.1. Adequate income to sustain operation obtained	Yes	Yes
4.2. Funding mechanisms in place for waste management	Yes	Yes
4.3. Funding mechanisms in place for long term spent fuel management and decommissioning	Yes	Yes
4.4. Civil liability for nuclear damage in place	Yes	Yes
Activity_M3-6.1: Ensure adequate financing and funding arrangements available for commissioning and operation of SMR/MMR **Activity_M3-6.1:** Ensure adequate financing and funding modes are in place for civil liability for nuclear damage **Activity_M3-6.3:** Ensure adequate funding in place for waste management and decommissioning of SMR/MMR. For decommissioning of MMR efforts and funding is minimal		
M3-5. Legal Framework		
5.1. Legal framework implemented and being reviewed as necessary	Yes	Yes
Activity_M3-5.1: Ensure National Nuclear Law is in place and enacted		
M3-6. Safeguards		
6.1. An SSAC that is operational for the nuclear	Yes	Yes

Nuclear Infrastructure	Small Modular Reactor (SMR)	Micro Modular Reactor (MMR)
power programme		
Activity_M3-6.1: Ensure SSAC roles and responsibilities are duly conducted, adequate staff and their training with required funding is available		
M3-7. Regulatory Framework		
7.1. Competent and independent nuclear regulatory body operating effectively	Yes	Yes
7.2. Management system in place	Yes	Yes
7.3. Regulations in place	Yes	Yes
7.4. Arrangements in place for cooperation with regulatory bodies in other countries	Yes	Yes
Activity_M3-7.1: Ensure Regulatory Body is functioning effectively with enough resources and management system in place **Activity_M3-7.2:** Develop relevant codes and standards for commissioning, operation and maintenance, safety and radiation protection, waste management and decommissioning		
M3-8. Radiation Protection		
8.1. Equipment for dose monitoring and control in place	Yes	Yes
8.2. Programmes to optimize doses from operation and maintenance in place	Yes	Yes
Activity_M3-8.1: Ensure operating organization staff is trained on usage of dose and radiation monitoring devices and other radiation protection devices, instruments are in place. **Activity_M3-8.2:** Evidence of Radiation Protection Team well qualified to optimize doses during operation and maintenance		
M3-9. Electrical Grid		
9.1. Interface between operating organization and grid company effective	Yes	May not be Required
9.2. Plans for grid enhancement executed	Yes	May not be Required
9.3. Grid reliability demonstrated	Yes	May not be Required
Activity_M3-9.1: Evidence on plans for grid enhancement executed by grid company and grid reliability demonstrated **Activity_M3-9.2:** Ensure that interface between operating organization and grid company is effective		
M3-10. Human Resource Development		
10.1. Ongoing human resource development programme in the operating organization	Yes	Yes
10.2. Ongoing human resource development programme in the regulatory body	Yes	Yes
10.3. National educational programmes and research and development to support capacity building implemented	Yes	Yes
Activity_M3-10.1: Ensure human resource development programme in the operating and regulatory body are in place and effective for current O&M of SMR/MMR and future SMR/MMR projects **Activity_M3-10.2:** Incorporate nuclear education in more universities and develop nuclear R&D centers to support capacity building and technology innovation		
M3-11. Stakeholder Involvement		
11.1. Transparent and open communications continue	Yes	Yes
Activity_M3-11.1: Ensure continuous and transparent public communication and engagement programme in place		
M3-12. Site and Supporting Facilities		
12.1. Confirm/update site characterization	Yes	Yes

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parameters and continue site monitoring		
Activity_M3-12.1: Continue site monitoring and update site characterization parameters		
M3-13. Environmental Protection		
13.1. Environmental limits and conditions defined	Yes	Yes
13.2. Environmental monitoring programmes in place	Yes	Yes
Activity_M3-13.1: Ensure environmental monitoring programme in place		
M3-14. Emergency Planning		
14.1. Owner/operator emergency arrangements in place and tested	Yes	Yes
14.2. Government and Regulatory body arrangements in place and tested	Yes	Yes
14.3. Arrangements for regular training, drills and exercises in place	Yes	Yes
Activity_M3-14.1: Ensure owner/operating organization arranges regular training in emergency planning, drills and exercise in place		
M3-15. Nuclear Security		
15.1. Physical protection system demonstrated and approved	Yes	Enhanced Security Needed
15.2. Contingency plan approved	Yes	Yes
15.3. Leadership and security culture evident	Yes	Yes
15.4. Preparation and approval of the security plan	Yes	Enhanced Security Needed
Activity_M3-15.1: Ensure nuclear security culture in place in both owner/operator and regulatory organization **Activity_M3-15.2:** Ensure enhanced security and physical protection system in place during construction and commissioning of SMR		
M3-16. Nuclear Fuel Cycle		
16.1. Arrangements for fuel supply in place	Yes	Yes *(MMR module will be changed every 10-30 years. Old module/spent fuel will be returned to the vendor.)*
16.2. Spent fuel management arrangements in place	Yes	
Activity_M3 -16.1: Ensure that nuclear fuel supply arrangements are done in timely manner		
M3-17. Radioactive Waste Management		
17.1. Plans for decommissioning available	Yes	Yes
17.2. Work to develop HLW disposal arrangements ongoing	Yes	Not Required
17.3. Arrangements for low and intermediate level waste in place	Yes	Yes
Activity_M3-17.1: Ensure construction of waste management facility for SMR are in line with international and national regulatory standards **Activity_M3-17.2:** Develop plans for future decommissioning and ensure necessary funds are allocated for SMR/MMR		
M3-18. Industrial Involvement		
18.1. Support for industrial development established	Yes	Not Required *(Unless vendor plans to manufacture MMR in the newcomer country itself)*

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Activity_M3-18.1: Extend support for industrial involvement during O&M, and future SMRs		
M3-19. Procurement		
19.1. Procurement capability for operations available	Yes	Yes
Activity_M3-19.1: Evidence of procurement capability during operation and maintenance available		