IAEA TECDOC SERIES

IAEA-TECDOC-1854

Deployment Indicators for Small Modular Reactors

Methodology, Analysis of Key Factors and Case Studies



DEPLOYMENT INDICATORS FOR SMALL MODULAR REACTORS

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IAEA-TECDOC-1854

DEPLOYMENT INDICATORS FOR SMALL MODULAR REACTORS

METHODOLOGY, ANALYSIS OF KEY FACTORS AND CASE STUDIES

> INTERNATIONAL ATOMIC ENERGY AGENCY VIENNA, 2018

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> © IAEA, 2018 Printed by the IAEA in Austria September 2018

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.

Title: Deployment indicators for small modular reactors / International Atomic Energy Agency.

Description: Vienna : International Atomic Energy Agency, 2018. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1854 | Includes bibliographical references.

Identifiers: IAEAL 18-01180 | ISBN 978-92-0-105718-1 (paperback : alk. paper) Subjects: LCSH: Nuclear reactors. | Nuclear energy. | Energy policy.

FOREWORD

Substantial progress has been made in many IAEA Member States in the development of small modular reactors (SMRs) as a potential option to enhance energy supply security in both developed and developing countries. In synergy with other available alternatives, SMRs can be considered as a future flexible energy source for generating electricity and industrial process heat, particularly for countries and/or sites for which large nuclear power plants would not be viable.

This publication provides IAEA Member States with a methodology to evaluate indicators for deploying SMRs in a national energy portfolio by analysing the key factors. It elaborates the specific attributes of SMRs and evaluates their deployment potential from the viewpoints of energy demand, finance and economics, infrastructure, climate change and energy security in an energy portfolio. The publication also uses case studies to illustrate the types of conditions that are potentially favourable to using an SMR.

This publication aims at giving Member States an enhanced capacity to apply a simplified process for country level self-assessment, with the flexibility to adapt to country specific needs. However, rather than attempting to determine or suggest whether SMRs should be adopted by a country, it provides a starting point for Member States to consider whether SMRs could be a suitable choice to meet their energy needs.

The IAEA wishes to acknowledge the assistance provided by the contributors and reviewers listed at the end of the report, especially the contribution made by D. Solan (United States of America) in conducting the initial study on the deployment indicators for SMRs with its associated methodology and analyses.

The IAEA officers responsible for this publication were D.E. Shropshire of the Division of Planning, Information and Knowledge Management and M.H. Subki of the Division of Nuclear Power.

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SUMMARY

The purpose of this report is to identify conditions amenable for the use of nuclear power by International Atomic Energy Agency (IAEA) Member States that are considering low-carbon energy strategies, and to discriminate specific conditions favourable for the adoption and deployment of small modular reactors (SMRs)¹. This report focuses on SMRs as advanced reactor designs that are: 1) 300 MW(e) and below; 2) modular; and, 3) manufactured and constructed primarily in dedicated facilities and then shipped to site for installation. As SMRs are emerging technologies that are nearing initial deployment, this report also defines and evaluates a set of broad indicators for SMR deployment. The report provides a starting point for Member States to use while determining if SMRs could be a suitable choice to meet their energy needs.

The report evaluates indicators within the following general categories.

- Energy demand (general and specific to SMRs);
- Finance/economics;
- Physical infrastructure;
- Climate change; and
- Energy security.

These indicators are expected to be generally applicable to the use of large and small nuclear reactors, however this report places emphasis on the specific attributes of SMRs. While Member States can use data sources that are generally available to the public to perform a self-assessment, this report considers options for them to customize criteria to further adapt the deployment indicators to their own specific needs and capabilities.

There are many alternatives to increase energy production — the nuclear alternative, in particular, is attractive because of its benefits relating to energy security, reliability, and environmental concerns such as climate change. Moreover, Member States have the option of considering the use of SMRs to match their varying energy and economic development strategies, even as they use large nuclear power plants (NPPs) to increase energy production. In fact, while many of the conditions needed for the development of NPPs are similar to those required for SMR deployment, the smaller size and broader range of outputs from SMRs can, in many cases, widen their placement options and provide increased opportunities for sustainable energy development.

This report is not a market report from the commercial perspective of the nuclear industry. It does not attempt to determine or suggest whether SMRs should be adopted by a country. Indicators described herein may be used as a starting point to customize for country-specific conditions using

¹ The IAEA uses the SMR acronym to refer to small and medium-sized reactors or small modular reactors. This report uses SMR only to refer to small modular reactors.

additional indicators and weighting factors. The SMRs may serve as an appropriate option for many countries in addressing Sustainable Development Goal (SDG) 7, i.e. providing affordable and clean energy. In countries lacking access to affordable, reliable, sustainable and modern energy, SMRs could be used in remote applications or where the electricity infrastructure may not be suitable for large NPPs.

1. INTRODUCTION

1.1. BACKGROUND

Small modular reactors (SMRs)² are an emerging technology that can play a role in meeting increasing global energy demands, stemming largely from population growth and the expanding needs of the developing world, including increased urbanization and industrialization. Meeting the higher demand for energy will require a better use of currently available energy sources, strategic changes in the energy mix being utilized, and the application of new energy sources.

Currently, there are around 20 primary SMR designs under development in 10 countries (Argentina, China, France, India, Italy, Japan, the Republic of Korea, the Russian Federation, South Africa, and the United States of America) for domestic energy production and, in the case of some designs, for commercial export. For the purposes of this report, the methodology and analysis focuses on the trend in SMR development as outlined by the IAEA:

"The trend in SMR development has been towards design certification of small modular reactors, defined as advanced reactors that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises. The driving forces in the development of such reactors are: meeting the need for flexible power generation for wider range of users and applications; replacing the ageing fossil-fuel fired power plants; enhancing safety performance through inherent and passive safety features; offering lower upfront capital cost affordability; suitability for cogeneration and non-electric applications; options for remote regions with less developed physical infrastructures; and offering possibilities for synergetic hybrid energy systems that combine nuclear and alternate energy sources, including renewables." [1]

Opinions vary widely on when new designs of inherently safe and economically viable SMRs will truly be ready for deployment. This uncertainty creates a dilemma for SMR developers who need reactor orders to make large investments in factory production, and for SMR customers, who need to know when SMRs will be available for commercial purchase and at what cost, before they can place an order. Most importantly, this uncertainty can impact the ability to plan for future improvements in meeting immediate energy needs as well as planning for optimizing the role of energy in future economic development.

Building upon previous work that incorporates economic impacts, [2] cost models, and preliminary methods to assess measures for the adoption of SMRs, [3] this report provides a summary review of deployment indicators for SMRs with a particular focus on developing economies. It has been prepared from a potential user perspective, rather than as a top-down volumetric market

² ibid.

assessment from a supplier's viewpoint. This report would thus enable IAEA to better assist Member States should they consider the adoption of SMRs.

A major differentiator for this report is the range of deployment indicators described. However, countries have not been assessed quantitatively due to potential sensitivities, although quantitative studies have been performed in other reports, using Analytic Hierarchy Process (AHP) rankings and using similar indicators [4]. Additionally, other contemporary studies have focused on market forecasting; [5,6] undertaken quantitative analysis using a limited set of indicators; [7] conducted analysis of a specific subset of countries of interest to the Government of the United States of America; [8] used a limited quantitative evaluation of factors or relied upon expert opinion on the subject. [9]

1.2 OBJECTIVE

The overall objectives that guide this report include the following.

- The inclusion of indicators that are transparent and applicable to as wide a user-base as is practicable.
- The inclusion of indicators applicable to the development of nuclear power in general, and to SMRs in particular.
- Reliance on data that is trusted and readily available.
- The use of cases, with examples, to illustrate the types of conditions that are potentially favourable to using an SMR.
- A simplified process for country level self-assessment, with the flexibility to adapt to country-specific needs.

Of the 18 indicators described in this report, 3 are associated with National Energy Demand (including the growth of economic activity, primary energy consumption growth, and energy consumption per capita); 3 are focused on specific SMR-related demands for distributed energy, cogeneration of electricity and heat, and energy intensive industrial processes; 3 relate to financial and economic sufficiency (including standard measures of Gross Domestic Product (GDP), international trade and foreign investment, and credit standing); 3 relate to Physical Infrastructure Sufficiency (measures of electric capacity, infrastructure capacity, and land availability); 3 are related to climate change (measures of the motivation to achieve climate goals, reduce carbon footprints and the dependence on fossil fuels); and the final 3 indicators are associated with Energy Security (and include reducing energy imports of fossil energy, balancing intermittent renewables and utilization of domestic uranium resources).

The IAEA Member States may use the deployment indicators to assess the potential applicability of nuclear energy technology, including SMRs, in their country. Analysis of the indicators is a

given freedom to Member States to determine. They may choose to put greater weighting on one indicator rather than another. They may decide to define a benchmark score for each indicator as a measure of sufficiency. They may also choose to compare or benchmark against the scores of other countries, e.g., indicator scores for the 30 existing nuclear states. Scores can also be normalized for each indicator (e.g., scores of 1 to 10) and totalled to yield an overall score for the Member State, to enable it to evaluate the degree to which deployment is viable within its energy development strategy.

Member States may consider creating regional groupings to combine resources to improve their SMR deployment potential and adopt SMRs. Three regional groupings are suggested below, as an example.

- Baltic countries: Estonia, Latvia, and Lithuania.
- Member States within the Gulf Cooperation Council (GCC): Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE).
- Member States in Southeast Asia: Brunei Darussalam, Indonesia, Malaysia, and Singapore.

The above groupings are meant to be a demonstration and not a prediction, suggestion or indication that these countries are currently pursuing SMRs. They were chosen because of a history of regional cooperation, an expressed interest in nuclear power, and because of potential SMR-specific applications particular to the grouping (district heating, desalination, and industrial processes).

Finally, this report suggests there may be necessary conditions that must be met before a country can realistically consider SMRs. Examples of potential must-pass conditions include a minimal electric grid size and minimal economic conditions. These are discussed at length, later in the report.

1.3. SCOPE

Member States have different needs and may, with regard to energy planning, stress the importance of certain factors such as international relationships, economics, geography, energy security, or natural resource endowment. This report will provide a quantitative and objective tool that can be used by Member States to assess: 1) whether SMRs provide a technology that can meet their energy needs; and 2) their readiness for the adoption of SMRs. This report will also provide a baseline for a future decision framework that provides for scenario analysis — through modification of indicators for a given Member State, or for potential improvement in certain indicators if a number of countries/Member States jointly pursue SMRs as a beneficial technology. In other words, it provides a foundation from which countries/Member States can assess the SMR option by customizing either the emphasis on given indicators or categories, or by simulating increased scores via simulated infrastructure improvements or via simulated activities targeted at increasing economic productivity.

This report would also assist the IAEA to identify Member States that will need further assistance in the development of a national infrastructure for nuclear power, using the IAEA's "milestone approach" [10] covering the necessary institutional, legal, regulatory and other relevant aspects to introduce any nuclear technology, including SMRs. It therefore addresses the recommendation made by the Standing Advisory Group on Nuclear Energy to the Director General of the IAEA in April 2013, advising the "Agency to stay abreast of information and developments related to, particularly, the demand for small modular reactors." Thus, this report will help IAEA to carry out its mission to assist Member States.

1.4. STRUCTURE

This report utilizes 18 indicators that provide a broad survey of a country's potential to adopt SMR technology. The indicators fall (3 each) into 6 main categories—1) National Energy Demand; 2) SMR Energy Demand; 3) Financial/Economic Sufficiency; 4) Physical Infrastructure Sufficiency; 5) Climate Change Motivation; and 6) Energy Security Motivation—as shown in Table 1.

| National Energy Demand | SMR Energy Demand | Financial/ Economic Sufficiency | Physical Infrastructure Sufficiency | Climate Change Motivation | Energy Security Motivation |
|--|--|--|---|---|--|
| Growth of Economic Activity (GDP GWTH) | Dispersed Energy (RURAL) | Ability to Support New Investments (GDP/PC-GDP) | Electric Grid Capacity (GRID) | Reduce CO ₂ Emissions per Capita (CO2) | Reduce Energy Imports (ENG IMP) |
| Growth Rate of Primary Energy Consumption (GRPEC) | Co- Generation (DESAL/DH) | Openness to International Trade (FDI/TRADE) | Infrastructure Conditions (INFRA) | Reduce Fossil Fuel-Energy Consumption (FOSSFUEL/OGC) | Use Domestic Uranium Resources (URAN) |
| Per Capita Energy Consumption (PC-EC) | Energy Intensive Industries (EII) | Fitness for Investment (CREDIT) | Land Availability (LAND) | Achieve NDC Carbon Reduction Goals (NDC) | Balance Intermittent Renewables (RES) |

TABLE 1. CATEGORIES AND INDICATORS

The first two categories—National Energy Demand and SMR Energy Demand—assess whether there is sufficient energy demand growth and need for SMR-specific applications. The next two categories—Financial/Economic Sufficiency and Physical Infrastructure Sufficiency—are used to assess financial capacity to support the high capital investment required for adopting SMR technologies, along with adequate physical infrastructure, and land. The final two categories— Climate Change Motivation and Energy Security Motivation—assess a country's motivation to reduce greenhouse gas (GHG) emissions, expand its low-carbon energy portfolio and utilize domestic natural resources, including uranium, for nuclear power.

With the exception of the second category—SMR Energy Demand—all the other categories include indicators that are, to a large extent, coincident with requirements or conditions favourable to the development of other large energy or electric generation infrastructure in addition to a nuclear-specific indicator (uranium resources). Each indicator should be considered independently, as each category is balanced by an equal number of indicators. There is also a balance between indicators across all six categories measuring energy demand, financial/economic/infrastructure sufficiency, and motivations to address climate change and energy security.

Data on the indicators are available from the World Bank,³ the Organisation for Economic Cooperation and Development (OECD), the United States Energy Information Agency (EIA), the World Economic Forum (WEF), IAEA, OECD's Nuclear Energy Agency (NEA), the University of Melbourne in Victoria, Australia (for climate classification), the United National Framework Convention on Climate Change (UNFCCC), United Nations Department of Economic and Social Affairs (UN DESA), and the International Energy Agency (IEA). Data sources for each indicator are provided in Appendix A, where they are updated periodically by the respective institutions.

A large number of indicators were originally investigated but not included in the preparation of this report, almost entirely due to limitations in data availability. These indicators included electric grid characteristics; number of domestic industries and local contributions to supply chain; energy demand forecasts; macroeconomic forecasts; technical and regulatory personnel proficiency; and financing models, among others. Care was also taken to eliminate redundant indicators during the selection of the indicators.

The indicators suggested in this report cannot be detached from the user's technical requirements for the power system. For instance, a country may require that before the SMR be deployed, it would need to: 1) demonstrate achievement of technical performance; 2) be based on an existing reference plant (typically in the supplier country); and 3) demonstrate successful operation for a minimum of five years.

2. OVERVIEW OF SMALL MODULAR REACTOR DESIGNS, APPLICATIONS AND DEVELOPMENT

This section provides a brief overview of SMRs, highlighting their distinctive characteristics as compared to traditional large NPPs, non-modular reactors below 700 MW(e), and fossil-fuel power plants. The specific design features and applications of SMRs are described along with a range of estimates for the economic viability of SMR deployment. This report assumes that the first commercial SMRs would become operational in the early 2020s, considering the current status of designs, engineering, and licensing processes of SMRs.

2.1. DESIGN FEATURES

Small modular reactors have several design features that differentiate them from other sources of power generation. In contrast to large nuclear or fossil-fuel generating facilities that typically have electricity output in excess of 700 MW(e), SMRs are relatively small, producing less than 300 MW(e). While globally there exist a number of designs and operating reactors that fall into the size range of SMRs, they lack the other characteristics associated with SMR design. Depending on the specific reactor design, SMRs are characterized not only by their size, but also by features

³ Data from the World Bank are constantly updated and refined, at least annually, often quarterly. Due to these data updates and refinements, data for historical and baseline years change with each update.

including integrated design, modularity of manufacture and installation, passive safety and heat removal systems, underground containment, and reduced fuel requirements. Recent publications by IAEA and others describe the SMR designs currently being developed for commercial deployment within the next decade. [11,12] Such designs include water-cooled type SMRs, with development underway in several countries including Argentina, China, India, the Republic of Korea, Russian Federation, United Kingdom and the United States of America.

There are several design features that make SMRs substantially different from the operating NPP designs. One of the key features is modularity in both manufacture and deployment. Manufacturing modularity has been adopted for large advanced water-cooled reactors in general. Aiming to shorten construction schedules, it provides the possibility for fabrication of the major components of the power unit—including the reactor vessel, steam supply, and cooling system—in centralized manufacturing facilities. For SMRs, due to substantially lower thermal power, the primary system's components can be integrated within or in the proximity with the reactor vessel, thus forming a reactor module that eliminates the need for large coolant piping. Once fabricated, these are shipped for on-site installation. This approach has several advantages, including standardization of both design and components, shortened site construction schedules, and results in economies of mass production.

In addition to the advantages associated with their small size and modular nature, SMRs have important design features related to passive safety, passive heat removal, design simplicity, and non-proliferation. Passive safety features enable SMRs to shut down automatically, while remaining cool without external power or operator intervention, for a much longer period of time than the operating conventional water-cooled reactor designs. Passive heat removal enables the reactor to remain cool by allowing cooling to take place through gravity, convection, and evaporation, and without the use of active pumps to circulate cooling fluid. Design simplicity is realized through a dramatic reduction in components as compared to large power facilities, and through the integration of primary systems into a single reactor vessel.[13]

2.2. ECONOMIC VIABILITY AND DEPLOYMENT

The simplified SMR designs result in a reduction in the number of components and a commensurate reduction in overnight costs. Further, the modularity of SMRs that enables the centralized fabrication of major components of the power unit has several advantages, including the standardization of both components and design, creating significant economies of mass production. As noted by Rosner and Goldberg, cost estimations for SMRs are significantly different than those for large NPPs in that scale economies are gained "through 'economies of mass manufacturing' where economy is achieved in the capacity and throughput at a dedicated SMR manufacturing facility rather than in the size of the fully deployed reactor site." [14]

Scale economies from modularization are anticipated to stem not only from mass manufacturing of component modules, but also from increases in productivity and efficiency gains as the

production of successive modules continues over time. The economies gained through mass manufacturing and learning are anticipated to result in SMRs being economically competitive with conventional nuclear facilities, and have been recently described as the "economy of multiples" of SMRs, counterbalancing the loss of "economy of scale" of larger nuclear facilities [15]. In addition to these scale economies, SMRs require shorter construction times compared to large generating facilities, which results in reduction of both long-term financing costs and schedule risks. Additionally, operating costs for nuclear, including SMRs have much lower sensitivity to fuel cost volatility than coal or natural gas. These factors, along with more efficient reactor fueling and lower maintenance costs, can result in very competitive levelized costs of electricity.

These cost advantages suggest that SMRs can be economically competitive with large NPPs, as well as with facilities producing energy production from fossil fuel or from renewable energy sources. Cost estimates vary widely however—recent overnight capital cost estimates include US \$5000/kW(e) for the SMART design, US \$4332/kW(e) for the NuScale design [16], and US \$5000/kW(e) for the IRIS design, implying that the levelized cost of electricity (LCOE) from SMRs may be cost competitive with generation from renewables, coal, and natural gas, depending on the location [17]. A 2013 study, based on the expert elicitation method, produced estimates ranging from US \$3200 to US \$16 300/kW(e) for a first-of-a-kind unit, depending on design and output [18]. Depending on the realized costs, the global and regional markets for specific applications may be only niche at the high end, or very significant at the low end. A more recent study sponsored by the United Kingdom estimated a very large market range—65–85 GW(e)—by 2035 [19].

These potential cost advantages extend beyond the initial deployment period of SMRs, in that SMRs are subject to much lower fuel price sensitivity risk than are large coal or natural gas facilities, because fuel costs comprise a much lower share of SMR operating costs than they do in the case of fossil fuel plants [20]. As a result SMRs are subject to far fewer changes in competitiveness, unlike gas and coal plants, which are impacted by changes in both fuel price and environmental regulations [21]. Therefore, through the deployment of SMRs, utilities in both large and small countries/Member States can better diversify fuel portfolios and mitigate the risk of fuel-cost volatility associated with coal and natural gas electricity-generation facilities.

2.3. SMR APPLICATIONS

The design features of SMRs enable a flexibility of implementation and variety of applications not found in large NPPs. These include incorporating SMRs into a variety of grid types and sizes, options for integration with renewables, non-electric applications, and security features. In terms of grid integration, the size and modularity of SMRs enable them to be part of smaller electric grids that serve a more dispersed population as compared with NPPs or fossil-fuel generating facilities. In addition, SMR modules can be integrated sequentially to provide progressive increases in energy production. For this report, an indicator with a small minimum grid size—as defined by IAEA—addresses these SMR attributes.

With the projected increase in the role of renewable energy sources over the coming decades, generating electricity from solar and wind technologies is becoming increasingly important. However, electricity grid managers are at a disadvantage with these technologies due to their variability in energy production. Trying to meet electricity demand in times of renewable oversupply or undersupply is further complicated and bound by regulatory and operational reliability rules and engineering constraints. The ensuing suboptimal results may include curtailment of renewables, load shedding, or maintaining thermal plants in abundant reserve at the cost of grid efficiency.

On the other hand, a key advantage of single and multiple module (from 2 to 12 modules) SMRs is their potential to balance fluctuating energy supply on the grid by varying electric production according to variability in conditions for wind or solar production. Flexible operations (shifting between electricity and heat production) and load-following capabilities of SMRs, are likely to be important for developing countries where increased generating capacity from renewables is projected to be more rapid than in more industrialized economies, or where countries are especially sensitive to energy imports or climate change impacts. Thus, this report includes a category of indicators for carbon reduction and energy security, to account for these SMR attributes.

Another important feature of SMRs is their potential use in non-electrical applications. While large nuclear and fossil-fuel plants are used almost exclusively to produce electricity, some innovative SMRs which operate at higher temperatures (e.g., gas-cooled high temperature reactors) have additional potential applications. Cogeneration applications for which SMRs are particularly suited are: 1) the provision of process heat for industrial applications; 2) district heating; and 3) thermal desalination.

Further, residual heat from SMRs is usable for a variety of industrial applications, including the production of glass, plastics, steel, synthetic fuels, and chemicals. The modularity and relatively small size of SMRs also offer advantages where process heat is needed, but not in the quantities associated with large nuclear or fossil fuel plants. Where high temperatures are not needed for industrial applications, SMRs are amenable to district heating applications, an application analysed as part of this report. In addition, the cogeneration of power and thermal desalinated water— using nuclear energy from SMRs is an attractive option in grids where desalination plants can utilize off-peak power [22]. According to an IAEA report [23], SMRs present the largest potential alternative to fossil fuel plants as cogeneration coupling options for desalination systems. Indicators for district heating, energy-intensive industrial sectors (especially those likely to be in remote areas) and other applications well suited for SMRs, are included in this report.

In addition to their size and modularity, the design and security features of SMRs make them amenable to markets that would not be suitable for large nuclear or fossil-fuel plants. Siting in locations other than near large bodies of water is made possible since the water required for cooling an SMR is significantly reduced. In addition, the passive safety systems of some designs allow SMRs to operate without external power or water sources and without human action for extended periods, enabling them to operate in locations where support systems are not well developed. Similarly, by constructing below grade level, the SMR security requirements may be less than for larger NPPs.

3. DESCRIPTION OF INDICATORS

The 18 indicators⁴ identified (and mentioned in section 1.1.), address a range of issues relevant to potential SMR deployment.

- The first two categories—National Energy Demand and SMR Specific Demand—cover the initial driver for consideration, i.e. the need or energy demand for specific applications or 'right-sizing' with regard to physical infrastructure, market, or geography for SMRs.
- The third category—Financial/Economic Sufficiency—addresses issues of feasibility, i.e. the ability of a Member State to economically support the deployment of SMRs.
- The fourth—Physical Infrastructure Sufficiency—addresses non-financial feasibility and includes indicators relating to grid capacity and other infrastructure, as well as land availability.
- The fifth category—Climate Change Motivation—addresses current energy-use factors as well as incentives to reduce greenhouse gas (GHG) emissions.
- The sixth and final category—Energy Security Motivation—addresses areas to increase energy security by adopting low-carbon energy sources and utilizing domestic energy resources.

Known possible data sources for the indicators have been provided in the footnotes. Appendix A of this report provides a consolidated list of indicator categories, indicator names, indicator symbols, and potential sources of data. Each of the indicators and the data sources used in this report are described in greater detail below.

3.1. NATIONAL ENERGY DEMANDS

There are three indicators within this category—Growth of Economic Activity (GDP GWTH); Growth Rate of Primary Energy Consumption (GRPEC); and, Per Capita Energy Consumption (PC-EC)—used to evaluate the overall national demand conditions increasing the chance for adoption of SMR-specific applications. These are discussed briefly below.

⁴ In some cases there is more than one measure available for a given indicator. These sources are listed as "optional" depending on the specific country situation, due to climate, economic, or other differences.

• Growth of Economic Activity (rate of real GDP growth (GDP GWTH))

- In addition to the overall size of a nation's economy and its per capita GDP, the rate of growth of economic activity is a key indicator of energy demand and of its ability to finance new energy sources. There are several relatively small economies albeit with a high rate of economic growth, interested in nuclear development programmes. Conversely, large economies with low rates of economic growth are less likely to have high rates of growth for new energy sources. High GDP growth rates signify that a country has increased employment, income, and overall economic activity, with a commensurate increase in energy demand and ability to accommodate SMR investments. A data source for this indicator is the World Bank [24].
- Growth Rate of Primary Energy Consumption (GRPEC)

The GRPEC is a measure that shows the relative change in demand for energy over time. Countries with higher rates of energy consumption are more likely to need increased access to energy and are, therefore, more likely to be receptive to new energy sources such as SMRs. This indicator was constructed by calculating the year-to-year growth rates of Total Primary Energy Consumption (TPEC in quadrillion⁵) from 2001 to 2011, years that had the most complete data available, and averaging those growth rates over that period [25]. Countries that have high energy-demand growth rates are deemed to be more likely to adopt SMRs than are those with stagnant energy demand.

• Per Capita Energy Consumption (PC-EC)

The PC-EC indicator is used along with others such as the GRPEC, to help assess the demand conditions of energy markets. Nations with high PC-EC rates are more likely to have increased energy needs in the future and, therefore, are more likely to acquire new energy production facilities such as SMRs. The data are given in kg of oil equivalent and the source for this indicator is the World Bank, with 2011 having the most complete recent data [26].

3.2. SMR ENERGY DEMANDS

The three indicators within this category—Dispersed Energy (RURAL); Cogeneration (DESAL); and, Energy Intensive Industries (EII)—are used to evaluate the demand conditions and to evaluate if conditions are amenable for adoption of SMR-specific applications. These are discussed briefly below.

• Dispersed Energy (percentage rural population (RURAL)) Given the characteristics of SMRs described in the previous section, electricity systems with a more dispersed generating capacity are more likely target markets for SMRs, than are more centralized systems. The RURAL indicator is used to measure market dispersion.

⁵ British Thermal Unit

It is calculated using the difference between total population and urban population in a country as a percentage of total population. The data source is the World Bank DataBank [27].

• Cogeneration (desalination capacity (DESAL) and, optionally, district heating (DH)) While large nuclear and fossil fuel plants are used almost exclusively to produce electricity, SMRs have potential additional applications. Principal among these are cogeneration applications including desalination and district heating. The indicator for the latter is discussed below. Small modular reactors can provide power for desalination in order to help alleviate water scarcity, especially in the developing world. As noted by the IAEA, desalination has the potential to be a leading use for the emerging SMR industry [28]. This is because desalination is an energy-intensive process and the cogeneration of desalinated water and power using nuclear energy from SMRs, is an attractive option in developing countries and in grids where desalination plants can utilize off-peak power [29]. Data for the DESAL indicator were obtained from Global Water Intelligence, a provider of analyses and data for the international water industry [30]. These data indicate additions to the desalination capacity of the top 30 countries globally and are, therefore, indicative of the growth of desalination demand for the countries listed.

The district heating indicator is used to assess a non-electric application for SMRs. District heating is common in cold to temperate regions and can be derived from a variety of heat sources. It is of particular importance where heat is required approximately 10 months per year due to geographic climate conditions, and especially so for areas where the coldest months have extreme low mean temperatures, or the summers are cold. The data used for this indicator are derived from an updated Köppen-Geiger scale that uses time-series temperature and precipitation observations to develop climate maps. The Köppen-Geiger scale and its variants have been in existence since the early twentieth century and are still used today by scientists. The University of Melbourne, Victoria, Australia, maintains data related to the updated climate classification system, which was published in a peer-reviewed journal in 2007 [31].

• Energy Intensive Industries (EII)

In addition to market dispersion, as measured by the RURAL indicator described above, countries with a significant reliance on EII sectors that are at a distance from centralized urban markets are likely to be good candidates for energy from SMRs. Data was obtained regarding energy use in EIIs that could use the electricity and process heat that an SMR is capable of generating. These industries are iron and steel, non-ferrous metals, pulp and paper, and mining and quarrying, as defined by IEA. Data for this indicator are derived from Sankey Diagrams, or national energy flows for select industries, based on IEA's *International Energy Statistics* [32].

3.3. FINANCIAL AND ECONOMIC INDICATORS

The three indicators in this category—Ability to Support New Investments (PC-GDP); Openness to International Trade (FDI/TRADE); and, Fitness for Investment (CREDIT)—are used to evaluate country-specific economic and financial conditions. These are discussed briefly below and also serve as proxies for the demand conditions of energy markets.

• Ability to Support New Investments (gross domestic product (GDP) and optionally per capita GDP (PC-GDP))

The GDP indicator is used to evaluate the SMRs need for energy as well as the ability to support investment in SMRs. This indicator captures the notion that larger economies have larger power requirements, are more likely to require multiple SMRs, and are better able to finance its purchase. The GDP—the total value of all final goods and services produced within a country in a given time period—is the most common measure of the size of a country's economy. The measure used here assesses GDP on an annual basis in terms of purchasing power parity (PPP) rather than nominal currency; GDP is often measured in current US Dollars (US\$) using nominal exchange rates between a country's domestic currency and the US\$. The use of PPP adjusts for disequilibria in exchange rates. The data for this indicator is from the World Bank DataBank [33].

The PC-GDP indicator is also used as a measure of a country's economic activity. It is calculated by dividing the GDP in terms of PPP by a country's population. It is used here as another measure of a country's ability to purchase SMRs. This is a standard measure of the level of economic well-being enjoyed by an average citizen in a country; and increase in per capita GDP (PC-GDP), indicates a commensurate rise in energy demand. Thus, higher levels of PC-GDP are likely to be associated with an increased demand for SMRs. As with the previous indicators, PC-GDP is measured in terms of PPP rather than in current US\$. The data for this indicator is from the World Bank DataBank [34].

• Openness to International Trade (foreign direct investment (FDI), FDI net inflows as a percentage of GDP and, optionally, international trade as a percentage of GDP (TRADE)). The FDI indicator measures net inflows of short- and long-term equity capital from foreign investors to acquire a lasting management interest in domestic enterprises in a country. The FDI net inflows in current US\$ measure new investment inflows, net of foreign disinvestment. As with the previous indicator, FDI measures serve as a proxy for the amount of trade flows that comprise a country's economic activity.

While TRADE measures the overall level of international trade, FDI measures the amount of foreign financial and physical capital entering a nation's economy on an annual basis. This serves to indicate the receptiveness of a nation to foreign investment and also the willingness of foreign entities to make investments in that economy. As with the following indicator, it serves as an indicator of the domestic financial and economic climate, and future country prospects. The data source is the World Bank DataBank for 2013.

The TRADE indicator serves as a proxy for the openness of a country's economy. Countries with high levels of international trade are likely to be more open to importing components for production of new energy. This indicator also measures the degree to which a country is integrated into the global economy. As noted by OECD, smaller economies are generally more integrated, as indicated by a higher share of international trade relative to GDP. As with the previous indicator, countries with smaller overall economies, but that are nonetheless growing and open to trade, are more likely to consider the deployment of SMRs than are slow growing, closed economies. The data for this indicator is from the World Bank DataBank [35]. It may be calculated by adding Merchandise Trade Percentage of GDP to Trade in Services Percentage of GDP.

- Fitness for Investment (External Debt/Credit Rating (CREDIT))
 - An important determinant of a country's ability to invest in new energy projects is its ability to obtain financing for such projects. A country with low external debt or a high credit rating is likely to be able to obtain such financing more readily and with lower interest rates. Given the size of investments in new energy production facilities, such as SMRs, relatively low interest rates make the overall costs of such facilities lower than would be the case if higher risk premiums were added to the interest rates on loans for these projects. Data on debt levels across countries is incomplete in nature. The two best available indicators are used. The first is the external debt stock as a percentage of GDP, which uses data from the World Bank DataBank as total current external debt in USD [36]. External debt is not available for all countries from this data source. An alternative measure of credit-worthiness, as given by Standard & Poor's credit rating system, is used where external debt is not available [37].

3.4. PHYSICAL INFRASTRUCTURE INDICATORS

The three indicators—Electric Grid Capacity (GRID); Infrastructure Conditions (INFRA); and, Land Availability (LAND)—are used to evaluate the size and type of a country's electric grid, the state of technology and availability of land. Since INFRA indicators are based on indices they therefore also cover other important issues such as technological readiness. These are covered by INFRA as described below.

- Total Installed Electric Grid Capacity (GRID)
 - The IAEA has issued guidelines regarding the size of electricity-generation units relative to total grid size [38]. Under these guidelines, the SMR unit size should be less than 10 per cent of total grid capacity. Thus, for smaller SMR designs of 150 MW(e), the electric grid capacity should exceed 1500 MW(e) or 1.5 GW(e). Those with grid sizes less than this limit should consider alternative power-generating facilities. Once that threshold is passed,

larger grids indicate an increased ability to accept SMRs. Thus, total electric grid size is one indicator of a country's ability to accept SMRs and the size of electricity market demand. The data source for this indicator is the EIA's *International Energy Statistics 2012* [39].

• Infrastructure Index (INFRA)

The INFRA indicator [40] measures national physical infrastructure on the basis of transportation, communications, and electrical distribution networks; this report also suggests a measure of the suitability of a country's technological conditions for SMR utilization. The data source for this indicator is the WEF's annual *Global Competitiveness Report*.

• Land Availability Index (LAND)

The LAND indicator [41] is associated with the land available for siting energy projects with access to utility systems. Regions with dense populations have limited space for distributed energy sources and require more compact power systems. Reduced land availability is a result of increasing urbanization, particularly in developing countries. Growth of industries and their concentration in urban areas is one of the major causes of rural-urban migration. As a result of industrialization, people from the rural areas move towards industrialized cities in search of income and employment thus increasing the population density and decreasing land available for energy production. The rate of urbanization is an important indicator. The data source for this indicator is the report on *World Urbanization Prospects* brought out every two years by the Population Division of the UN's Department of Economic and Social Affairs.

3.5. CLIMATE CHANGE INDICATORS

In addition to the other categories, it is important to assess the incentives for a country to adopt SMRs and, by doing so, reduce climate change from continued fossil fuel usage, and meet goals in country National Determined Contributions (NDC). The three indicators used here—CO₂ Emissions Per Capita (CO2); Reduce Fossil-Fuel Energy Consumption (FOSSFUEL/OGC); and, Achieve NDC Carbon Reduction Goals (NDC)—are discussed briefly below.

• CO₂ Emissions Per Capita (CO2)

The CO_2 indicator assesses a country's motivation for adopting low-carbon emissions energy production. The indicator used here, CO2, [42] serves to gauge the likelihood that a country is incentivized to reduce such emissions in order to address climate change concerns, and it is a proxy for other GHG emissions. Therefore, countries with high levels of carbon and other GHGs are deemed more likely to be amenable to SMR adoption. The data source for CO_2 emissions per capita is the World Bank DataBank. • Reduce Fossil-Fuel Energy Consumption ((FOSSFUEL) and, optionally oil, gas, and coal as percentage of total electricity capacity (OGC))

The FOSSFUEL indicator measures coal, oil, petroleum, and natural gas products used as fuels for energy production. As with the above indicators, countries with high reliance on fossil fuels are deemed to be more likely to be incentivized to reduce emissions from these sources. Further, as climate change concerns are likely to lead to regulatory incentives to reduce emissions, including GHG emission taxes or capture and storage requirements, these energy sources will become more expensive. Thus, increased reliance on these fuel sources is anticipated to be positively correlated with likely SMR adoption. The data source for this indicator is the World Bank DataBank [43].

The OGC indicator addresses the issue that countries, heavily reliant on high carbon sources of electricity production, may be more likely to implement fuel-switching or at least increase their electricity production using low carbon sources, because of the long-term need to address climate change and pollutants. This could be renewables, such as wind and solar energy, as well as nuclear energy. 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. The measure used in this report is 'oil, gas, and coal as a percentage of total electricity capacity [44]. This measures the following inputs used to generate electricity: oil (crude oil and petroleum products), natural gas (excluding natural gas liquids), and coal (both primary and derived coal fuels) as a percentage of total electric capacity.

• Achieve NDC Carbon Reduction Goals ((NDC) and, optionally, country-specific energy plans)

The NDC indicator assesses a country's motivation for adopting low-carbon emissions energy production. The indicator used here, GHG Target Goals [45] serves to gauge the motivation of a country to reduce GHG emissions in order to address climate change. Therefore, countries with more aggressive reduction goals are deemed more likely to be amenable to SMR adoption. The data source for GHG Target Goals is the UNFCCC NDC Registry.

Another measure of carbon reduction comes from country energy plans to retire existing fossil power plants (particularly coal power) or to build additional fossil to meet energy shortfalls. Individual country energy plans are the source for this indicator.

3.6. ENERGY SECURITY MOTIVATION INDICATORS

Another incentive for using SMRs is to reduce the risks related to energy security. Three indicators used here—Reduce Energy Imports (ENG IMP); Use Domestic Uranium Resources (URAN); and, Balance Intermittent Renewables (RES)—are described in brief below.

- Reduce Energy Imports (percentage of energy use (ENG IMP))
 - The ENG IMP indicator addresses the notion that countries that import a large percentage of their energy are more likely to be interested in developing domestic energy production and are thereby more likely to be potential markets for SMRs. In this measure, 'energy imports as a percentage of energy use' [46] are estimated as the difference between energy use and energy production.⁶ A country with a positive value uses more energy than it produces and is, therefore, a net energy importer.
- Use Domestic Uranium Resources (URAN)
 - The URAN indicator is used for those countries with demonstrated uranium resources that are likely to be economically viable to extract over the short- and medium-term. The indicator is a measure of the uranium resources in a country estimated by IAEA to be economically extractable at a price of US \$130 per kg or less. Many of the countries with such domestic uranium deposits have expressed an interest to engage in nuclear development programmes such as the deployment of SMRs. The data source for this indicator is the "Uranium 2014: Resources, Production, and Demand Report", also known as the Red Book, jointly produced by the OECD's NEA and the IAEA [47]. Countries should also consider that IAEA will host a Low Enriched Uranium (LEU) Bank as an assurance of supply mechanism of last resort, and will be a physical reserve of LEU available for eligible IAEA Member States.
- Balance Intermittent Renewables (RES) The RES indicator [48] is used to assess increased shares of renewable energy requiring

⁶ Both of these measures are given in oil equivalents.

backup and balancing from other energy sources. With the rapid growth of renewable energy due to government support in many countries, more flexible energy sources including SMRs may be increasingly needed to make up for energy supplies when the wind is not blowing and the sun is not shining. Many SMRs are being designed to ramp up power when demands surpass renewable supplies and to cogenerate heat when renewables are available. The data source for this indicator is the IEA forecast on renewable energy growth.

4. ANALYSIS OF SMR FEASIBILITY USING INDICATORS

This section of this report provides a description of how the indicators may be assessed to determine relevance for SMR deployment. The concluding sections of the report discuss potential approaches for countries to perform their own assessment and further customize the evaluation using country-specific data.

4.1. MULTI-CRITERIA DECISION ANALYSIS

There are several approaches to making decisions using multiple indicators or criteria. These approaches fall under the general category of Multi-criteria Analysis (MCA). In the recent SMR deployment studies cited earlier in this report, smaller sets of criteria were used to evaluate prospective countries for possible SMR deployment. The market assessment report by the United States Department of Commerce (DOC) [49] employed 8 criteria to evaluate a pre-selected set of 27 countries. The DOC report used a quartile system to rank countries in terms of their market feasibility for SMRs. The system ranked countries into quartiles for each criterion and gave them a corresponding score, with a score of 4 given to those nations ranked in the highest quartile and a score of 1 given to those in the lowest quartile.

A report by Black et al. [50] used the Analytic Hierarchy Process (AHP) to evaluate SMR feasibility using 15 criteria for 97 countries.⁷ The AHP method has been used extensively since its development in 1990 in decision-making research involving energy development, [51] including energy source selection [52]. While AHP is widely used for decisions involving both quantitative and qualitative criteria, the report by Black et al. found that similar results were obtained using a decile ranking system. As AHP methodology requires sophisticated analytical techniques, the purchase of licenses, and costly programming, the present report employs a decile system to evaluate SMR deployment indicators. The analysis performed by Black et al. revealed that the results varied significantly between a quartile and decile assessment system. The quartile system favoured countries with very large economies more heavily.

⁷ The report began with a sample of 214 countries, which had to satisfy 5 necessary conditions in order to be further evaluated; 117 countries failed to meet these conditions.

4.2. OPTIONAL CONDITIONS

A useful framework for further analysis is to consider possible necessary conditions for nuclear power development. Countries may want to consider the imposition of initial and high-level "gate" conditions that must be passed through for SMR adoption to be practicable. In most cases, it is possible to address these conditions as they are not necessarily permanent.

The first of such conditions considers the size of the electric grid in a Member State. The IAEA issued guidelines for the size of electricity generation units relative to total grid size [53]. Under these guidelines, the SMR unit size should be less than 10 per cent of total grid capacity. For a smaller 150 MW(e) SMR, the electric grid capacity should exceed 1.5 GW(e). Thus, one of the potential 'must-pass' conditions is that a Member State should have a total grid size exceeding 1.5 GW(e). As with the indicator GRID, described above, the data source for this necessary condition is the United States' EIA [54].

In addition to electrical grid capacity, sufficient economic and financial resources to invest in nuclear energy technologies can be considered. Countries with low levels of overall economic activity are unlikely to have the necessary demand and financial conditions necessary for utilizing either large NPP or SMRs. As an example, the country with the lowest GDP of all countries with a nuclear programme under development is US \$20.2 billion (PPP). As with the GDP (PPP) indicator, the data source for this indicator is the World Bank [55]. Alternatively, a country may consider more international, new arrangements including Build Own Operate and Transfer (BOO-T) and public-private partnerships. These arrangements may particularly help those developing countries which may not have a sufficient base for independent financing of a nuclear construction project. The vendor country takes on the financial risk and becomes the source of capital, thus reducing the threshold on financial readiness.

In addition to the level of overall economic activity, the demand conditions within a country increase with PC-GDP. Therefore, a third possible condition that a country can consider is to achieve a sufficient level of per capita income measured by PC-GDP (PPP). The country with the lowest PC-GDP with an ongoing nuclear power development programme was US \$2588 (PPP) in 2011. Thus, a logical potential minimum for a Member State to be considered for SMR development is a 2011 per capita GDP exceeding US \$2588. The data source here, as with the PC-GDP indicator, is the World Bank [56].

A country can include additional conditions in its assessment that it considers necessary for a nuclear power programme (e.g., related to size, transport access, etc.).

4.3. ANALYSIS INSIGHTS

This report identifies characteristics specifically favourable to the deployment of SMRs. These include SMR-specific indicators in the SMR Energy Demand category, particularly those that

identify site-specific and often energy intensive applications, as well as those countries with relatively dispersed populations.

Countries with strong economies, a high reliance on fossil fuels, sufficient grid capacity, high energy-consumption growth rates, and high levels of GHG emissions are often seen as good candidates for SMRs. However, these conditions, in and of themselves, are not likely to be sufficient for differentiating between markets suitable for large NPPs and those that are more suited for SMR deployment. In this regard, the spatial distribution of the population may play a role. Some countries may be well-suited for new sources of low-carbon electricity production. However, due to the concentrated nature of their energy demand and electricity load centres, they may be better suited for large NPPs than for SMRs. Similarly, the presence of domestic cost-effective uranium resource deposits will positively influence a country's consideration for nuclear power but is not a requisite for SMR deployment.

Poor economic and physical infrastructure conditions typically characterize countries less suitable for SMR use. Such conditions include small grid sizes less than 1.5 GW(e); insufficient energy demand favourable to SMRs (such as for desalination or for energy intensive industries); and insufficient economic conditions (that may be apparent from low levels of GDP and PC-GDP).

The World Bank classification of countries by income provides a useful framework for characterizing market viability. As of July 2014, the countries classified by the World Bank fall into four principal income groups: low income (US \$1045 or less), lower middle income (US \$1046-4125), upper middle income (US \$4126-12 745), and high income (US \$12 746 or more). The measure of income used in this classification system is Gross National Income (GNI) per capita,⁸ adjusted to reduce the impact of exchange rate fluctuations across countries by using the World Bank Atlas Method conversion methodology [57]. Many countries classified as low-income and low middle-income countries by the World Bank have economic conditions characterized by low scores for the GDP and PC-GDP indicators. This may signal an insufficient market size to support SMR deployment as well as limited ability to finance the high capital investment required to deploy and operate SMRs.

4.4. REGIONAL GROUPINGS OF COUNTRIES

An important consideration in planning an energy future is the degree to which a Member State chooses to enter into partnerships with other countries. In terms of meeting increased energy demand through the use of SMRs, partnering is especially important. By entering into power generation and sharing agreements, several countries that individually are not likely to invest in SMR development activities can, as a group, combine resources to build a SMR. Three groupings are suggested as a demonstration or representative examples of the effects such cooperative

⁸ It should be noted that, while the World Bank classification is based on GNI, this report uses GDP at PPP as a measure of income. Exchange rate fluctuations were accounted for using the PPP measure for both GDP and PC-GDP.

arrangements can have on the likely deployment of SMRs. It is important to note that these groupings have not been chosen based on the likelihood or appropriateness of SMRs being deployed versus other technologies, nor have they been chosen because the necessary government-to-government agreements are easy or quick to facilitate or implement. In fact, they may be lengthy and very difficult.

In addition to the Baltic states of Latvia, Estonia, and Lithuania, these possible groupings include the Southeast Asian countries of Brunei Darussalam, Indonesia, Malaysia, and Singapore; and the Persian Gulf countries of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates UAE. Although not analysed here, similar connections also exist between Croatia and Slovenia, the northern African countries of Algeria, Libya, and Tunisia, with a planned interconnection with Italy [58], and other regions across the globe.

Countries considering the development of SMR capability jointly, are likely to consider the total size of their combined electric grids, level of economic activity, and uranium resources. For example, in purchasing, lending, and power-sharing agreements, it can be stipulated that the country with the highest level of credit, transparency, ease of doing business, etc. be designated the controlling party. An advantage of grouping is that the financial risk is shared among partners.

Two challenges are relevant to the regional groupings of countries in order to undertake joint development of SMRs. First, it should be noted that orchestrating cross-border investments as well as purchasing and power-sharing arrangements is a particularly complex, and significant issue that cooperating countries will have to address. For countries to collaborate on the purchase of an SMR, they will need to develop the expertise necessary or partner with the more experienced States to ensure they are able to obtain the requisite financing as well as meet the lending prerequisites that may require changes to national laws to comply with international treaties and global safety and security standards. The second issue is to note that although commercial banks, multilateral development banks (MDBs), and export/import agencies have funded nuclear projects in the past, they have been reticent to finance current NPPs. The rationale for not participating in such arrangements relates to the high initial capital costs, lengthy construction period, underestimation of actual final costs, delayed financing returns, and—in the case of MDBs—sensitivity about financing nuclear power.

To a large extent, the design features of SMRs may help to mitigate many of these financing risks. In addition, the technology can be integrated with other sustainable energy sources. Further, demand can be met incrementally thereby allowing for sequential investment. Therefore, while countries within regional groupings face the necessity of higher levels of coordination and collaboration, it is also anticipated that group purchasing of SMRs within a region may be an acceptable investment by commercial banks while it would require a change in outlook by MDBs and some export/import agencies.

5. OPTIONS FOR DATA CUSTOMIZATION

5.1. MEMBER STATE REFINEMENT OF INDICATORS

The indicators described in this report, the supporting data for each indicator, and the overall methodology have been developed to aid countries in conducting a pre-assessment of the degree to which SMRs might form part of an overall energy development strategy. While the suggested indicators are of value, they can be improved through customization for country conditions using additional indicators and data sources.

On an absolute scale, a Member State can assess its own energy demand conditions as well as economic, infrastructural, and carbon reduction amenability. Each Member State may want to assess its relative readiness compared to other countries. Relative readiness is important because of the newness of SMR technologies and the uncertainty surrounding cost and performance of the first few units. As more countries adopt the technology, the indicators and methodology developed here will be refined. Potentially, more certainty may be developed over time as to specific technologies (e.g., reactor type, reactor output, fuels) adopted by a country, its characteristics (e.g., size of grid or the manufacturing base), and use (e.g., electricity, district heating, cogeneration, desalination, hybrid, etc.). Indicators may also be updated, added, or deleted depending on their explanatory value.

6. CASE STUDIES

6.1. GENERIC DEPLOYMENT CASE STUDIES

To facilitate further understanding and use of the methodology, this section provides six generic deployment case studies that represent a broad range of deployment conditions, including electric and non-electric conditions. These cases illustrate the variety of conditions under which countries may choose to deploy SMRs. For example, a country that is experiencing rapid economic growth and industrialization is different to one that has modest growth in energy demand but needs to replace an ageing fleet of fossil fuel plants for carbon reduction requirements. The case studies may be useful to countries in understanding their unique position in terms of energy needs, economic conditions, and legal infrastructure as they pursue pre-assessment of SMRs as an energy technology.

The representative case studies are listed below.

- Emerging Industrialized Economy, Large Land Area
- Emerging Industrialized Economy, Small Land Area
- Highly Developed Infrastructure Economy
- Rapid Growth Economy
- Desalination
- SMR Vendor Country

Case 1: Emerging Industrialized Economy, Large Land Area

The SMRs are an attractive deployment option for Emerging Industrialized Economies. These countries are characterized by high economic growth and growth in energy demand and a satisfactory foundation in physical and legal infrastructure. In addition, they have growing populations and rising incomes. They may have growing manufacturing and/or resource extraction industries that have intense energy demand, or the potential to develop them. Resource extraction industries may be distributed in rural areas where existing physical infrastructure and energy demand are limited. It is important to differentiate between two types of countries for this case: large and small.

The geographic land area of the country may be large, with a large population distributed unevenly. Electric infrastructure and transmission are also concentrated unevenly across the land mass or between islands in certain countries. The SMRs are an attractive option for countries with unevenly distributed populations and grids with low interconnectivity as they do not have the large grid size requirements of a traditional NPP, and SMRs represent an attractive option to increase electricity generation capacity to meet growing demand. Manufacturing often represents an important segment of the economy of countries in this category, and SMRs can provide the process heat used in many industrial applications.

Energy-intensive industries have good potential for coupling with SMRs if they are at a distance from an existing electrical transmission infrastructure or urban markets. The baseline model includes an indicator for these industries that could use electricity and/or process heat that an SMR is capable of generating, and the indicator score specifically analysed the presence of iron and steel, non-ferrous metals, pulp and paper, and mining and quarrying industries. Other industries that utilize process heat but do not have data available for this indicator include glass, plastics, hydrogen production, synthetic fuels, ammonia and other chemical manufacturing.

Case 2: Emerging Industrialized Economy, Small Land Area

Emerging industrialized countries with small land area are likely to have a more export and tradedriven economy due to a lack of diversity in natural resources. While these countries may have the domestic grid-size to accommodate SMRs, they are likely to be more tied and dependent on a regional grid. Like large countries in this category, States with a small land area are also characterized by growing PC-EC. They may have abundant oil and gas resources and thus have a history of relying on them. For those that do not have petroleum resources, they are very likely to rely on energy imports. As with the larger states, SMRs are a fit for either electricity generation or process heat for industrial applications, or both. The heavier reliance among many of these countries on a regional shared electrical grid, emphasizes the need for regional cooperation and planning. For other countries that may not have robust ties with neighbouring countries, the opportunity to deploy SMRs may provide the impetus to strengthen the electrical infrastructure between the States and thereby improve energy security. For these small countries, cooperating regionally and sharing investment and electrical infrastructure makes a stronger case for SMR and other technology deployment options, compared to pursuing them individually. Regional collaboration may provide opportunities to improve conditions in regard to energy demand, physical and legal infrastructure, and the overall size of combined economies. In addition, these countries often do not have an abundance of fresh water, and tend to have high population densities. Therefore, they may consider the deployment of SMRs for electric power or for an application such as desalination.

Case 3: Highly Developed Infrastructure Economy

These countries are characterized by well-developed economies and physical infrastructure, with periods of high economic growth and the installation of electricity generation and transmission infrastructure occurring substantially in the past—on the order of at least forty years ago. They do not have significantly increasing electricity demand in the future without the development of new industries that may lead to increased consumption.

The SMRs must compete with other technologies to replace physical infrastructure that is approaching end-of-life or obsolescence due to insufficient pollution controls or the expense of updating plants, such as those that are coal-fired. Additionally, such countries may pursue deployment of SMRs for industrial process heat or desalination depending on resource endowment and significance of energy intensive industries. Decarbonization may be a policy concern, in which case SMRs represent a source of carbon-free baseload generation, and high temperature designs may play a role in research regarding hydrogen production and synthetic fuels.

Countries in this category may have an existing nuclear programme, and therefore issues related to the deployment of any nuclear technology may be comparatively easy for them. Developing the personnel, expertise, and regulatory structure necessary for nuclear power, a significant undertaking for countries without experience with nuclear power, would be less onerous for these countries.

Case 4: Rapid Growth Economy

There is a wide diversity among these countries, characterized by periods of rapid growth in GDP and primary energy consumption that may be inconsistent over time. Additionally, these countries may have underdeveloped energy infrastructure and periods of political instability or oscillations in government openness to markets in the recent past. Many countries in this category do not have experience with nuclear energy. In rapid-growth economies, a non-traditional financing model of

deployment such BOO-T could be attractive if the necessary physical infrastructure for deployment exists alongside a climate conducive to business.

Many countries in this category lack both legal and physical infrastructure; others possess one but not both. Countries may have natural resources that are not fully utilized, and they may be moving to a more open market economy and upgrading infrastructure. These countries might focus efforts to raise their capability to deploy SMR technology through natural resource and industry development. In addition, governmental efforts to raise per capita incomes and overall GDP can be achieved through investment in human, legal, and capital infrastructure. These countries should align their energy planning with IAEA nuclear milestones if they wish to pursue SMRs. For the international community, deployment of SMRs in these countries may be part of a larger strategy to provide electricity access to those who currently do not have it. The SMRs may be an attractive deployment option to match rising electricity demand, the development of new industries, energy intensive applications, and the electric infrastructure as it is built out.

Case 5: Desalination

Those countries already pursuing desalination of seawater to meet demand for fresh water may consider the deployment of SMRs for desalination. Countries facing water scarcity or those projected to experience water scarcity may also consider the deployment of SMRs for this purpose. Countries with these requirements are highly diverse. Some are arid states with significant and highly developed petroleum production infrastructure, and access to capital. Other countries have large geographic areas with diversity of climate and water distribution. They are also diverse in terms of their economic capacity. Still others are geographically small, with poor resource availability in both water and energy.

Case 6: SMR Vendor Country

Those countries that have or are producing SMR designs are seeking to deploy them for domestic energy production, export, or both. Many of the designs are based on light water reactor technology. A number of designs, all in the advanced category, include high temperature reactors intended for process heat applications in addition to electric generation.

The countries for this case are fairly diverse although there are a limited number of them. Some are traditional large NPP developers that continue to be involved in the commercial or civilian nuclear industry after many decades. These countries have deployed NPPs domestically and sold for export, in addition to investing in SMR development. They continue to view SMRs in these terms. Others seek to develop a domestic SMR design as key for national economic development, in concert with domestic energy needs. Exports are a secondary consideration but still may be pursued if successfully deployed domestically.

APPENDIX

DATA SOURCES BY CATEGORY

| Category | Indicators | Symbol | Dataset | Data Source |
|--|--|----------|---|---|
| National Energy Demand Indicators | Growth of Economic Activity | GDP GWTH | GDP Growth (annual %) | World Bank DataBank |
| | Growth Rate of Primary Energy Consumption | GRPEC | Primary consumption 2001 to 2011 (Quadrillion Btu) | US Energy Information Administration, International Energy Statistics |
| | Per Capita Energy Consumption | PC-EC | Energy use (kg of oil equivalent per capita) | World Bank DataBank |
| SMR Specific Demand Indicators | Dispersed Energy (Rural) | RURAL | Rural population (% of total population) | World Bank DataBank |
| | Co- generation | DESAL | Annual increment to contracted capacity forecast (2007–2016 average) | Global Water Intelligence's DesalData |
| | Co- generation | DH | Köppen Climate Classification | KOTTEK, M., J. GRIESER, C. BECK, B. RUDOLF, RUBEL, F., 2006: World Map of the Köppen-Geiger climate classification updated [59] |
| | Energy Intensive Industry | EII | Energy use in iron and steel, non-ferrous metals, mining, and pulp and paper (thousands of tons of oil equivalent, ktoe) | International Energy Agency, World Energy Flows |
| Financial/ Economic Sufficiency | Ability to support new investments | GDP | GDP, PPP (current international \$) | World Bank DataBank |

| | Ability to support new investments | PC-GDP | GDP per capita, PPP (current international \$) | World Bank DataBank |
|--|---|-----------|---|--|
| | Openness to International Trade | TRADE | Merchandise trade (% of GDP) | World Bank DataBank |
| | | • | Trade in services (% of GDP) | World Bank DataBank |
| | Openness to International Trade | FDI | Foreign direct investment, net inflows (BoP, current US \$) | World Bank DataBank |
| | | • | GDP, Current US \$ | World Bank DataBank |
| | Fitness for Investment | CREDIT | External debt stocks, total (DOD, current US \$) | World Bank DataBank |
| | | • | S&P ratings index | Standard & Poor's Ratings |
| Physical Infrastructure Sufficiency Indicator | Electric Grid Capacity | GRID | Total electricity installed capacity (million Kw) | US Energy Information Administration, International Energy Statistics |
| | Infrastructure Conditions | INFRA | Infrastructure (rank) | World Economic Forum Global Competitiveness Report |
| | Land Availability | LAND | Urbanization rate | UN DESA |
| Climate Change Motivation Indicator | Reduce CO2 Emissions per Capita | CO2 | CO ₂ emissions (metric tons per capita) | World Bank DataBank |
| | Reduce Fossil Fuel- Energy Consumption | FOSS FUEL | Fossil fuel energy consumption (% of total) | World Bank DataBank |
| | Reduce Fossil Fuel- Energy Consumption | OGC | Electricity production from oil, gas and coal sources (% of total) | World Bank DataBank |

| | Achieve NDC Carbon Reduction Goals | NDC | Nationally Determined Contributions | UNFCCC NDC Registry |
|---|---|---------|---|---|
| Energy Security Motivation Indicator | Reduce Energy Imports | ENG IMP | Energy Imports, net (% of energy use) | World Bank DataBank |
| | Utilize Domestic Uranium Resources | URAN | Uranium identified resources (Reasonably Assured Resources and inferred), < \$130/kgU US \$ | International Atomic Energy Agency |
| | Balance Intermittent Renewables | RES | Increasing share of renewable energy | IEA Medium- Term Renewable Market Report |

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ABBREVIATIONS

| AHP | Analytic Hierarchy Process |
|---------|--|
| BOO-T | Build Own Operate Transfer |
| BoP | Balance of Payments |
| BTU | British Thermal Unit |
| CAES | Center for Advanced Energy Studies |
| СМ | Consultancy Meeting |
| CO2 | Carbon Dioxide |
| DOC | Department of Commerce |
| DSS | Decision Support System |
| EIA | Energy Information Administration (US) |
| EII | Energy-Intensive Industry |
| ENG IMP | Energy Imports |
| EPI | Energy Policy Institute |
| GCC | Gulf Cooperation Council |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gases |
| GNI | Gross National Income |
| GRPEC | Growth in Primary Energy Consumption |
| GW(e) | Gigawatt electric |
| GW(th) | Gigawatt thermal |
| IAEA | International Atomic Energy Agency |
| IEA | International Energy Agency (autonomous body linked |
| | to OECD) |
| kg | Kilogram |
| Ktoe | Thousand Tons of Oil Equivalent |
| kW | Kilowatt |
| kW(e) | Kilowatt electric |
| LCOE | Levelized Cost of Electricity |
| MCA | Multi-Criteria Analysis |
| MDB | Multilateral Development Banks |
| MS | Member State |
| MW(e) | Megawatt electric |
| NEA | Nuclear Energy Agency (OECD) |
| NPP | Nuclear Power Plant |
| NPT | Non-Proliferation of Nuclear Weapons Treaty |
| OECD | Organisation for Economic Co-operation and Development |
| PC-EC | Per Capita Energy Consumption |
| | i ei Capita Energy Consumption |

| PPP | Purchasing Power Parity |
|--------|--|
| SMR | Small and Medium-sized Reactor or Small Modular Reactor |
| | Reactor |
| TPEC | Total Primary Energy Consumption (in quadrillion BTU) |
| UNFCCC | United Nations Framework Convention on Climate Change |
| WEF | World Economic Forum |

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International Atomic Energy Agency Vienna ISBN 978-92-0-105718-1 ISSN 1011-4289