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Socio-economic Potential of Micro Molten Salt Reactors

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1. Introduction

As the Paris Agreement to prevent global warming was concluded in December 2015, the world entered a new global regime that limits carbon emissions. Despite representing low-carbon energy, nuclear power generation has not been expected to increase its market. It is likely due to the concern of nuclear accidents and proliferation. On the other hand, human civilization becomes globally more digitalized, the demand for small-scale decentralized or off-grid energy markets is increasing with the growth rate of 9% annually. Micro nuclear reactors (hereinafter referred to as 'MNRs') have reemerged to cope with this rapidly changing business environment of energy sector while working on overcoming the drawbacks of existing large-scale light water nuclear power plants and meeting well the small-scale energy markets. Among them, micro molten salt reactors (hereinafter referred to as 'MSRs') are expected to be one of the safest and most nuclear-resistent. In this context, this study examined whether commercial micro MSRs will be able to secure socio-economic competitiveness, from the perspective of sustainable development, in small decentralized off-grid energy markets by the early 2030s

2. Business Environment of Micro Nuclear Reactors

The Fukushima nuclear accident raised anxiety about the safety of large nuclear power plants, which in turn led to the search for intrinsically safe alternatives such as MNRs. In this study, the micro nuclear reactor is defined as a very small-scale nuclear reactor that is used to produce electricity output of less than 30 MWe or heat output of less than 100 MWth. As of April 2021, 30 MNRs are being developed worldwide and mostly under the development of design. Globally, the first commercial demonstrations of MNRs are expected to be operational in the United States and Canada by the late 2020s. However, it is worthwhile to note that the future market of MNRs is still uncertain. According to Lee (2021), which supplemented the study of NUVIA (2016) that analyzed MNR market for the UK government, the MNR market for 5 years from 2031 to 2035 is expected to form a very wide range from a minimum of 2,125MWe (425 units of 5MWe-class MNR) to a maximum of 5,495MWe (1,099 units). Lee (2021) made this prediction based on two scenarios. First, the 'social scenario' represents that the public acceptance lowered by the 2011 Fukushima nuclear power accident will not be improved yet by the early 2030s. Therefore, the potential markets for MNRs are limited to mainly existing off-grid markets such as remote locations and military bases, which are predicted to form the size of 2,125MWe (425 units of 5MWe-class MNR). Second, the 'economic scenario' denotes that the socio-economic functions of MNRs such as nuclear safety and non-proliferation are socially accepted. In this case, the demand for MNRs will increase significantly in not only off-grid but also on-grid energy markets where energy security is more important than economics, such as defense facilities, industrial complexes, emergency power facilities, and strategic facilities in public and private sectors. As a result, the potential market for MNRs is expected to expand to 5,495MWe (1,099 units of 5MWe), about 2.5 times larger than that of the social scenario.

3. Analytical Methods

This study is concerned primarily with what functions and performance are required for MNRs to secure their market competitiveness in terms of economic profit and social acceptance and contribute to the sustainable development of mankind. To answer this question, first, this study identifies some indicators which makes up a conceptual framework, as seen in Figure 1, to cope with three major business environments such as the global movement of sustainable development, the structural change of energy markets and the industrial experience of nuclear energy production.

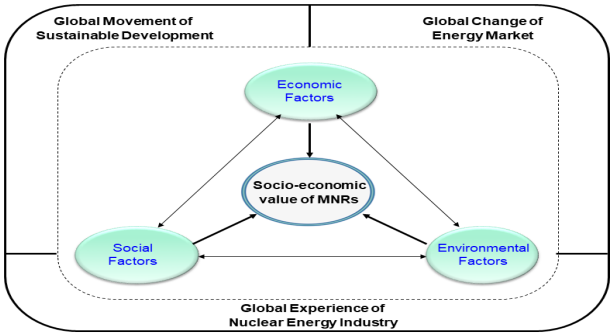

Figure 1. Conceptual Frameworks

In order to examine the socio-economic potentials of MNRs, this study developed a set of MNR indicators by applying general indicatiors of nuclear energy production for sustainable development to market requirements of MNRs. First, this study reviewed indicators to evalute nuclear energy for sustainabled development on the basis of conventional literature published by international organizations, such as Organization for Economic Cooperation and Development/Nuclear Energy Agency (NEA), Paul Scherrer Institute (PSI) and International Atomic Energy Agency (IAEA). However, most of existing literature, did not handle the issue on technology unit but on geopolitical one, mostly nation state. For example, some of energy indicators such as energy intensity and diversification in the IAEA et al. (2005) are not likely to be relevant for the level of technology Terefore this study reclassifies existing indicators to conform to the unit of technoloical system. Second, specific socio-economic requirements of MNRs need to be understood for their success in the markets, which will be unlike those of large nuclear power plants. To do this, this study reviewed existing studies regarding the socio-economic feasibility of MNR projects for the US Department of Defense, the Ontario government in Canada, and the UK government. By integrating general indicators of nuclear energy for sustainable development at the level of technical unit rather than

geopolitical one with specific market requirement of MNRs, this study identified a set of indicators which will be useful for socio-economic appraisal of micro molten salt reactors.

Tabel 1. MNR Indicators for Socio-economic Success

Indicators		Operational Definitions
Radiological safety	Inherent passive safety	Possibility of no radioactive material released out of the system to external environment; Possibility of complete removal of decay heat; Radioactivity released to ext. environment [Bq/year]
Non-proliferation	Proliferation resistance	Amount of sensitive nuclear material that can be discharged from the operation of MNRs [tU/MWh]
Off-grid energy supply	Energy security	Amount of time for non−stop operation of MNRs [year]
	Load following	Amount of time for MNRs to adust output to meet changes in demand [Day]
	Co−generation	Possibility of supplying both heat and electricity
Cost efficiency	Energy productivity	Amount of fuel per unit energy production [tU/MWh]
	Energy production cost	Leveled Cost of Energy (LCOE) [$/MWh]
	Recyclability	No of recycling reactor
Space efficiency	Miniaturization efficiency	Size of plant footprint per unit energy production [m^2/MWh]

4. Socio-economic Potentials of micro Molten Salt Reactors

The MSR is expected to be among the safest nuclear reactor conceptualized up to now in the world. First, the nuclear fuel is always cooled and never melt down. Second, the fuel salt has a great capacity to accommodate the temperature rise (600 to 700℃), Third, the cooling function of MSRs generally operates stably under atmospheric pressure. Fourth, MSRs can continuously remove most of radiation sources, or fission products generated by nuclear fission during the operation of the reactor. Fifth, MSR using chlorine salts and fast neutrons can burn almost all of the TRU materials and weaken their toxicity while producing energy during the long period of operation.

With a long cycle of nuclear fuel replacement, MSRs will carry very low risk of nuclear proliferation. During the operation, MSRs particularly using chlorine salts and fast neutrons, like Terrapower's Molten Chloride Fast Reactor (MCFR), could burn in principle 100% of sensitive plutonium that can be used as nuclear weapons. Thus, plutonium is almost completely incinerated over a long lifetime of the reactor operation and hardly discharged out of the reactor.

As for off-grid energy markets, MSRs with chlorine salts and fast neutrons could are understood to operate for more than 10 years without stopping nuclear reactor and replacing nuclear fuel, which can greatly increase the reactor availability and consequently improve economics. MSRs using liquid fuels could respond to load fluctuations very quickly. Since MSRs operates at a very high temperature of about 700°C. they can be used to produce a variety of energy for energy islands, such as electricity, heat, hydrogen production, seawater desalination, etc. The inherent feature makes MSRs more energy efficienty that it could increase thermal efficiency up to 50% which is about 1.5 times higher than that of the light water reactor (33%). MSRs need very little the so-called safety subsystem which accounts for about 30% of the construction cost in case of large LWRs. MSRs do not need large-scale complex facilities for the transmutation and/or the and final disposal of long-life high-level radioactive materials which require huge costs. Taking advantage of all these economic attributes, it is predicted that the micro MSR cost half as much as the conventional large LWRs. According to IEA (2021), the LCOE of nuclear power generation is estimated at about $65~120/MWh in 2030 when large LWR still occupies the majority. In contrast, the LCOE of micro MSR, which is expected to be commercially deployed in the early 2030s, is estimated to be about 31$~65$/MWh. Last, the MSR can greatly reduce the size of plant space for the same output of energy. Coupled with high passive safety as well as high energy efficiency, it consists of relatively small the reactor structure and the heat transfer systems as there is no need for a nuclear fuel transfer space and control rod guide tubes on the top of the reactor structure.

5. Conclusions

From the perspective of sustainable development, this study predicted whether commercial micro nuclear reactors (MNRs) can secure socio-economic competitiveness in the small decentralized energy markets by the early 2030s. Based on the literature review, this study developed an analytical method with a conceptual framework and relevant indicatiors which include radiological safety, proliferation-resistence, off-grid energy supply, cost efficiency and space efficience. For the practical purpose, this study assessed that micro molten salt reactors currently under the early stage of technology development would be likely to meet the socio-economic requirements and secure competitive advantage in their markets. The results of this study could provide both suppliers and potential users with strategic directions to success in their business. However, in order to increase the reliability of this result, it is necessary for mpirical studies that analyze related cases in a quantitive manner from the perspective of sustainable development

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