# Preliminary Study of SMR Competitiveness Evaluation Against Large Reactors

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## 1. Introduction

As small modular reactors (SMRs) are getting more attractive over the years, many countries tend to make research on SMR and large reactor (LR) competitiveness to make reasonable investment. As IAEA pointed out, several countries are developing transportable nuclear power plants, including marine based floating and seabed based SMRs. In 2019, floating type nuclear power plant (NPP) Akademik Lomonosov was connected to the electricity grid in Russia and started commercial operation [1]. Due to less experience in SMR field, the studies made in this field are crucial due to constitute a comprehensive guide for owner and contractor countries. In this research, SMRs will be evaluated against large reactors in terms of different factors as governmental, commercial, technical and external environment factors including their sub-factors considering present and after 10-year investments of energy generation sources.

## 2. Method

One of the well-known Multi Criteria Decision Making (MCDM) technique, called as Analytic Hierarchy Process (AHP), is planning to be used to make a decision and prioritization among factors which are most issued in literature. After selecting 4 factors and 17 sub factors, they were discussed with some experts in nuclear energy field to clarify and also approve the factors' reflecting actual issues between SMRs and LRs. These factors will prepare a baseline for AHP survey to apply experts in both nuclear energy and SMR field.

### *2.1 Competitiveness factors*

Factors affects SMR and LR deployment were clustered in 4 groups as governmental, commercial, technical and external environment factors with their sub factors as shown in Table 1. In addition, while determining these factors and their sub factors, the possible changes in 10 years were considered. Then, factors were formed to be able to identify the change of factors' effect on deployment of both SMRs and LRs in years.

#### 2.1.1 Governmental factors

These factors are related to governmental participation, and gathered in 5 category as political support, financial support, regulation and licensing process, national industry participation and public acceptance.

Government's political aspect has strong effect on deployment of nuclear energy sources, and these factors' effects may change according to different countries. Political support is related with government energy policy which addresses the issues related to energy growth and usage. Current and long-term energy policy would impact the selection of energy source According to different government policies, while some countries focus on climate and social issues (conditional) such as supporting low carbon energy resources; some would focus on more technical issues such as power output. For example, due to the increase of Japan's carbon intensity on energy supply, Japan head for renewable and nuclear energy. So, each country could have its own dynamics, and it reflects to the energy policy which is related to political support of government on nuclear energy. Furthermore, government energy policy is related to electricity demand of the country. When demand is predicted as huge and needed to be met, government tend to use LRs.

Table I: Competitiveness factors for evaluating SMR and LR

| Tier-1 factors | Tier-2 factors |
|---|---|
| Governmental | Political Support |
| | Financial Support |
| | Regulation and Licensing Process |
| | National Industry Participation |
| | Public Acceptance |
| Commercial | Design Cost |
| | Construction Cost |
| | O&M Cost |
| | Fuel Cost |
| | Economies of Scale |
| Technical | Safety |
| | Construction Duration |
| | Improved Quality |
| | Licensing Challenges and Schedule |
| External Environment | Electricity Market Demand |
| | Private Bankability |
| | Interest rate |

From the nuclear energy aspect, LRs can meet demand better compared to SMRs due to its large output. On the other hand, SMRs could be better to meet gradual demand due to its ability to module addition after construction. Except energy policy and demand, international and national relations of government, industry relation and long-term country goals are important for political support in nuclear energy resource selection. In addition to this issues, LRs are known with their cost overruns and delays which make them risky [2]. However, this does not mean they will not be accepted. Locatelli and Mancini show that LRs are more preferrable from the political aspects [3]. Therefore, both designs have both advantages and disadvantages from the government perspective.

A nuclear power plant project is characterized by high upfront capital costs and long construction periods, low and stable operational costs, and lengthy payback periods [4]. These commercial aspects make NPP project financing crucial which can be supported by either government or private financing. Government involvement in a project usually makes it much easier to raise cost-effective debt considering interest rate. Although most of the NPPs were financed by government, it typically takes place in the markets where governments are also involved in owning and operating energy utilities. So, government financial availability has effect on ownership which has great effect on government international image. Due to expected less construction time of SMRs which refers to less construction cost and shorter payback period, SMR deployment could increase government participation compared to LRs [5]. Although it depends on different countries' financial availability, ownership of SMRs could be easier for governments.

Many factors would affect SMR licensing and regulatory elements. Adapting current regulations to SMRs still in planning process. Due to their unique design features, the applicable codes and standards will need to be updated [6]. It is still uncertain which factors will affect getting SMR licensing more. Firstly, countries usually have licensing process for large reactors, and not familiar with SMR licensing. Consequently, this can lead delays for SMR deployment which can decrease SMR competitiveness financially and needs faster licensing processes for government [7], [8]. Also, SMRs has higher licensing cost per KW, compared to LRs because of their smaller size. Unfortunately, building more SMRs does not have proportional decrease on licensing cost. So, it is better to evaluate licensing cost of first of a kind (FOAK) is independent of the size. On the other hand, SMRs' designs are safer compared to LRs. So, this situation decreases the needs of emergency planning zone and some siting requirements. As a result, licensing process could be easier in terms of safety in SMRs [9].

National industry participation is related with both available facilities and industry level in the country to support nuclear energy. In terms of facilities, countries' available fuel cycle facilities, spent fuel and radioactive waste management facilities, security and physical protection levels, and laboratories could be considered. On the other hand, for industry level, different companies related to nuclear power such as engineering, manufacturing, construction and assembly, operation maintenance, and technical support are pointed for national NPP support [10]. These factors are important to participate in nuclear power generation for government image; however, involvement level must be decided. Too much national participation could lower the quality and result in worse effect on construction because of not having experience on NPP construction before [11]. Furthermore, much participation can cause cost overruns and schedule delay due to the necessity of educating national labors for vendor. So, government should participate in appropriate level.

Public acceptance can also change depending on different countries. This factor is considered in the scope of non-financial parameters; however, it also has effects on manpower support, site selection, construction processes which factors are related with financial parameters.

Public acceptance is expected to be improved in SMRs due to their security improvement, environmental impact improvement, proliferation resistance improvement, passive safety system and massive deployment [12]. Even if large reactors have already bad reputation in the scope of public acceptance, SMRs could fall lower than LRs due to their new system. If public resistance is high on LRs, government make decision on SMRs, otherwise in terms of large output and cost efficiency, LRs can be selected.

2.1.2 Commercial Factors

Although governmental factors are crucial for deployment, some quantitative factors should also be considered. There are many different factors related to costs in SMR deployment. In this paper, design cost, construction cost, O&M cost, fuel cost, and economies of scale are selected to evaluate.

Design cost is related with indirect costs and engineering design costs which support construction activities [13]. Study [2] stated that while some NPP designs have more effect on construction cost, some of them will have less effect which means the design differences may cause unexpected cost increase. Even if design changes cause delays and cost overruns, on the other hand, improvements may have positive effects, such as having cost advantage in nuclear power generation due to improvement in nuclear reactor design and optimization of plant layout for South Korea [14]. However, this situation may differ for each country, such as US and France's design innovations increased the construction costs. Even though specific costs are not pointed out in recent studies detailly; cost of research, development, and design for LRs is estimated between $1-$2 billion [11]. On the other hand, although there is no specific estimated cost for SMR designs, there are some studies to give overall idea for investors and researchers. Study [13] indicates that SMRs can achieve a 20% decreasing effect on cost comparing to LRs. On the other hand, these cost changes may not be happened in the first construction. Due to FOAK and nth of a kind (NOAK) SMR constructions, industry needs more time and experience to achieve these cost increases, and this process will affect the selection of the best time for SMR investment for investors.

Construction cost in SMRs projects gains more importance from the perspective of owners and investors [15]. In terms of size and modular components, SMRs are expected to have lower construction costs. Moreover, due to their easy manufacturing, transportation, and assembly, SMRs seem more competitive [11]. Some studies pointed out that SMRs could have 10%-20% reduction on construction costs [8]. However, in case of FOAK SMR, initial costs can be higher because of deployment of new technology. In the scope of this study, ten years projection will be useful to differentiate FOAK and NOAK costs. On the other hand, for large reactors, the highest part of cost is construction cost. Because LRs have to deal with some challenges such as construction complexity, cost of materials, transportation of major and large components to the construction site, and usage of labor. These costs make the selection of LR deployment disadvantageous. Despite these cost breakdowns, when it comes to ten years projection as in the scope of this study, modularization techniques are used in large reactors to make construction less complicated could contribute construction cost of large reactors as SMRs [11].

O&M cost is one of the biggest uncertainties for SMRs. There are many studies which estimate O&M cost of SMRs. Some studies indicate that SMRs might reduce O&M cost 10-20% [16]. On the other hand, for same size of power output, some studies argue that SMR will be more expensive as 19% [12]. Furthermore, in the study [31] the cost combination of O&M and fuel cost of LRs is indicated from $19/MWh to $21/MWh. Nuclear Energy Agency determined the mean O&M costs for large reactors as $14.66/MWh in 2011. In the same study, O&M cost is determined together with fuel cost between $7.1 and $36.2/MWh for SMRs. This study also indicates that O&M cost can change depending on FOAK and NOAK units. This means depending on experiences cost can be decreased. From this point, it can be thought that in 10 year projection, it could be possible to bring cost decrease on SMR case [19]. Moreover, it is expected that SMRs will have less O&M costs due to their small size, however, it is also uncertain due to not having an SMR in commercial operation [32].

The fuel cost is the sum of all activities related to the nuclear fuel cycle such as enrichment of uranium, manufacture of nuclear fuel, reprocessing of spent fuel, and any related research activities [17]. While construction cost and O&M control the investment decision in the short and medium terms, fuel cost is important for the long term [18]. SMR designs maximize the utilization of fuel, simplify refueling process, and reduce refueling frequency [6]. According to a study made in 2014, for some different reactor types, fuel costs were calculated. Overall, for LRs projected cost was calculated as 3.86 $/MWh, while SMR fuel cost is between 3.95 and 7.47 $/MWh which indicates 15%-70% increase on SMRs fuel cycle [18]. In another study, the total fuel cycle cost for SMRs is predicted as $9.33/MWh, while Chinese design HTR-PM has $10.90/MWh fuel cycle cost [19]. Therefore, uncertainties in SMR fuel costs gives different outcomes.

Economies of scale represents the decreasing on the cost by producing more which emphasized to having more benefits for larger plants over small plants in NPP projects [18]. According to a study made in 2010, when reactor size is decreased from 1340 MWe to 335 MWe, the specific decommissioning cost increases three times. This implies that increasing the reactor size has decreasing effect on specific costs [20, 21]. On the other hand, when the number of SMR module increased, unit cost of SMR is expected to decrease due to cost impacts on unit energy output (MW) with the total production and total radioactive waste. However, studies show that economy of scale tends to disfavor SMRs compared to LRs [22]. In addition, SMRs favor the economy of multiplies, rather than economy of scale. Economy of multiplies might be expressed as mass production which is also connected with learning effect in SMRs [21]. Furthermore, selection of LRs and SMRs also depends on demand. With a large energy demand such as 10 GW, LRs could have cost decreasing effect in terms of economy of scale. When the demand is less than 1 GW, SMR would be better considering economy of scale effect. If 1-2 GW is needed, both may be possible, but it should be considered according to country dynamics and other related factors such as financing, license challenges, and public acceptance.

### 2.1.3 Technical Factors

As technical factors, safety, construction duration, improved quality, licensing challenges and schedule were evaluated.

LRs have reliable safety features. However, SMRs are smaller in size than LRs, hence the magnitude of an accident could be reduced. The simplified design in SMRs also includes passive safety features which means no operator action is required and there is no dependency on external power to cool the reactor core. Not only safety system, but also smaller radioactive inventory, underground construction, innovative components (such as internal steam generator and pressurizer), use of additional fission product barriers also favors the SMRs safety. As a result of these, government can eliminate or reduce the requirements for emergency planning zone [9]. Most crucial effect focuses on the modular design of the nuclear steam supply system (NSSS) module. This eliminates external coolant loop piping and large-break loss of coolant accident (LBLOCA). In addition, the passive engineered safety features (ESFs) eliminate the need for external power under accident conditions [6]. Although SMRs have reliable safety and decreased probability of loss of coolant accident, a study made in USA indicate that LRs are still favorable for deployment in terms of safety and seen as optimal choice over SMRs [11]. The reason why LRs are selected is they already have proven quality and safety features. For both government and investors, LRs seem as low risky due to past experiences, even SMRs seem more reliable. So, LRs should be considered how to increase safety level to compete SMRs. As safety is crucial factor for deployment, it may affect some other factors such as licensing and public acceptance [1].

Delays are one of the most common issues in nuclear power plant construction projects. Due to spreading over a long time period, NPP projects are sensitive for construction delays which also affect directly labor costs and equipment costs due to high interest rates. On the other hand, it is crucial to point out construction duration independent from the construction cost, due to SMRs' unique technical issue. Although construction duration can also affect construction cost, cost part is more related to material, equipment and labor costs. In terms of SMRs, work conditions in a module factory are better and productivity is improved. Moreover, critical path activities decreased, and with the reduced size and design simplification assembly tasks can be performed concurrently which reduces total construction time onsite. So, construction times can be reduced by 25%–50%, depending on the project [8]. Recent studies show that multiple SMRs may better deal with construction delay than a single LR, when delay is longer than 1 year. However, when delay is more than 2.7 years, SMR also struggle to deal with this delay [23]. Studies show that SMR can be built in 3-4 years with extensive modularization which is 6-7 years for LRs [8]. In LRs case, when delay occurs, all capital investment cost is affected and increases proportionally to the delay time.

Modular construction techniques would affect quality. So, SMRs are expected to improve quality, offer more efficient balance-of-plant construction on site, and may reduce overall costs [24]. Quality would affect performing construction processes such as concrete pouring, welding, and steel cutting in a more controllable factory environment. Modular design will also reduce the number of components, minimize interfaces, reduce the number of workers on-site, and improve access and construction safety which are related with the construction quality [8]. However, due to the compact nature, SMRs may be challenging in terms of inspections, operations and maintenance both in construction and operation processes which could also affect quality. LRs may also be improved quality by applying modularization in some parts of nuclear power plant to increase operation simplicity, and quality.

Licensing is not only a governmental issue but also technical issue. In terms of technical part, SMRs are not commercially operating yet, so it will be uncertain issue for both delay and cost overrun. However, some issues are given as different licensing issues from LRs licensing; smaller power output - lower decay heat, fully passive safety features, modular design (multiple reactor modules, factory production), mass production (standardized design), serial construction (many plants in series) [33]. Due to its new design and technology, licensing of SMR would take more time or can cause more challenge comparing to LRs. In addition, the cost of licensing for the FOAK is almost independent of the size, therefore, the cost per kW is higher for SMRs with respect to LRs because of their reduced power output [7]. Moreover, it is stated that SMRs licensing can cause delays easily compared to LRs which already have more clarified procedures.

#### 2.1.4 External Environment Factors

External factors are considered as electricity market demand, private bankability and interest rate.

While SMRs can be attractive in terms of many technological and economic aspects, LRs are comparable due to their large output. SMRs might be thought as losing the benefit of economy of scale due to the lower electrical output per reactor [6]. On the other hand, SMRs allow to make incremental capacity addition, it could have a chance to support meeting the energy demand [25]. As of 2020, around 30 countries are currently considering or embarking on nuclear power and working with the IAEA, and United Nations predicting that the world's population will grow to 8.7 billion by 2030 [26], the demand for energy may also be likely to increase over this period. It means NPP projects and their demand could increase. Considering that all countries may not be ready for SMR technology, they may prefer LRs instead of SMRs [27, 28]. Furthermore, depending on countries' demand, SMR or LR may be preferred. For relatively larger demands such as more than 1GW, LR can give better solutions. However, if the demand less than 1GW or around 1GW, LR can be risky. In this case SMRs could give better response to demand in terms of cost efficiency. It is also necessary to point out that electricity demand is subject to change for each country. Therefore, evaluating this factor depends on country perspectives.

Bankability refers to attractiveness of project for the investors both public and government in terms of risk and return [29]. Due to SMRs' small size, short construction schedule, and lower capital cost, they may be seen advantageous by investors. However, they are not totally proved in terms of licensing and construction risks. In addition, multiple SMR units could have challenge for their upfront investment when compared to LR's power output. Moreover, public acceptance also can impact on project bankability. If public supports the project, bankability of the project will increase. On the other hand, large reactors need higher amount investments and longer construction time. From the perspective of private investors, this amount of money is crucial to take risk, especially considering the construction time. Although this investment also has risks, compared to SMRs, the process of deployment LRs is more certain due to its references all over the world, even if they have complicated construction processes.

Interest rate is more important for construction period which is the longest part of NPP projects, and this interest rate is called as interest during construction (IDC). IDC is an additional cost that included in total capital cost and function of capital cost and construction lead time which is defined as first pouring of concrete to start of commercial operation [19]. When schedule delay increase, IDC can be a big burden for high levels of capital at risk which could also affect the LCOE between 8% and 10% [30]. In terms of SMR projects, it is expected that modularization will decrease construction schedule. So, it may seem that due to decreased SMR schedule, IDC will affect the capital cost less [15]. Large reactors have longer construction schedule around 6 years which is almost double when compared to SMR construction schedule. When only construction schedule is considered, it can be predicted that LRs cause higher effect on capital cost in terms of IDC. Overall, compared to SMRs, LRs has more weakness when high interest rates are observed in the market.

### *2.2 AHP survey and expert selection*

A survey will be conducted to evaluate all these factors and sub-factors among each other for both SMRs and LRs. AHP is planning to use as decision making method, therefore 1-9 scale will be used for pairwise comparison. Experts will be selected due to their year of experiment, fields (related to SMRs or nuclear energy) and their country. So, it will be possible to evaluate some factors which can be changed due to different country situation such as political support and demand.

### *2.3 Comparison between current and 10-years later*

In this study, the contribution is thought as comparison of present and 10-year later. For this reason, sub factors will be compared in terms of both SMRs and LRs considering present situations and 10-year projections. So, this research might provide a beneficial results and foresights for future investors who wants to analyze competitiveness of SMRs and LRs.

## 3. Conclusions

As a result, this study will provide which option (SMRs or LRs) is reasonable for investment depending on time period from different aspects. Also, results will be explained from the perspective of owner and contractor to indicate strength and weakness of SMRs and LRs. These results will make contribution in terms of evaluating SMR deployment from the different perspectives.

This study is based on preliminary thesis study. Results are planning to be explained in conference presentation, as they will be analyzed.

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