CONSIDERATION OF LEVELIZED COST OF ELECTRICITY AND INVESTMENT RISKS OF SMALL MODULAR REACTORS IN EMERGING COUNTRIES

Kampanart Silva, Pidpong Janta, Nuwong Chollacoop

[1] *National Energy Technology Center (ENTEC), National Science and Technology Development Agency (NSTDA) 114 Thailand Science Park Phaholyothin Road, Klong Nueng, Klong Luang, Pathumthani 12120 Thailand,*
kampanart.sil@entec.or.th, pidpong.jan@entec.or.th, nuwong.cho@entec.or.th

ABSTRACT

Global commitment towards net-zero emissions led to increasing interests of newcomers in nuclear power. Southeast Asian countries are particularly interested in small modular reactor (SMR) due to its claims for better safety, better flexibility, better economic performance, and lower financial risks. The levelized cost of electricity (LCOE) for nuclear power is lower than many alternative sources in some countries, though it is much higher in other countries. This study aims to identify crucial factors affecting LCOE of SMR and understand their tendencies in emerging countries, in order to gain accurate perception of investment risks of SMR. Insights on factors affecting LCOE are gathered from historical records of LCOE of nuclear power and cost projections in energy outlooks and preceding studies. LCOE of nuclear power in developing countries is typically low due to lower material and labor costs. Countries with multiple types of reactors and more stringent regulations tend to have higher LCOE. While large reactors benefit from economy of scale, SMRs are expected to benefit from economy of multiples. LCOE of SMR will be much higher in the beginning and gradually decrease with multiplication over time. SMR will also have lower financial risk since it has smaller capital cost per unit. Additionally, LCOE in emerging countries may vary according to markup from exporting countries and options for backend management. Strategies for emerging countries to reduce LCOE and minimize investment risk include wait-and-see approach, gradual localization, and negotiation at regional scale.

Keywords: levelized cost of electricity (LCOE), small modular reactor (SMR), financial risk, economy of scale, economy of multiples

I. INTRODUCTION

Global commitment towards net-zero emissions led to increasing interest in nuclear power, and the number of newcomer countries expressing the eagerness to go nuclear is the largest in history. 25 countries from four continents, including newcomer countries, jointly launch declaration to triple nuclear energy capacity by 2050 at COP28 in United Arab Emirates in 2023 [1], and six more nations endorsed the declaration at COP29 in Azerbaijan in 2024 [2]. The International Energy Agency (IEA) [3] noted that nuclear generation is set to hit an all-time high in 2025. Around 420 reactors are in operation and an additional 63 with total capacity of roughly 70 GW are under construction. SMR is said to be the catalyst for the world's transition towards nuclear power.

Southeast Asian countries are particularly interested in deploying SMR, including Indonesia, Malaysia, the Philippines, Thailand, and Vietnam. Many of these have already included SMR in their national energy plan, including Thailand that included two 300 MWe SMRs at the end of the latest draft national energy plan. SMR is claimed to have enhanced safety through the adoption of the latest technology, better flexibility due to its modularity, better economic performance from economy of serial production, and lower financial risk due to lower upfront capital cost [4].

The lower levelized cost of electricity (LCOE) of nuclear and the lower financial risk of SMR have been the two crucial selling points of SMR in emerging countries. For example, a representative of Federation of Thai Industries expressed support for the inclusion of SMRs in the national energy plan as they can cut the electricity unit price by half [5]. As there are only two operating SMRs to date, the narratives on LCOE of SMRs have been built upon the LCOE of conventional nuclear power plants. The LCOE for nuclear power is lower than many alternative sources in some countries while statistics also show that it can be much higher than other sources in other countries. To create a fair ground for discussion of LCOE of SMRs, this study aims to identify crucial factors affecting LCOE of an SMR and understand their tendencies in emerging countries.

II. METHODOLOGY

This study employs exploratory research to clarify factors that affect levelized cost of electricity (LCOE) generated from a small modular reactor (SMR) project in a newcomer country and factors that affect investment plan of the project. Information is gathered from historical records of project investment cost (overnight cost), fuel cost, operation and maintenance cost (O&M cost), decommissioning cost, and any other costs that may occur throughout the project from energy outlooks, international reports, news, and preceding academic studies. Note that the majority of the information is still based on large nuclear power plants as there are still only two SMRs in operation to date. Factors are then synthesized from the pool of information considering two aspects: (1) effects on any elements of LCOE, and (2) effects on investment model, capacity, and schedule of SMR projects.

III. RESULTS AND DISCUSSION

III.A. Overnight cost remains the largest component of LCOE, but it might not be as large as expected in some countries.

Fig. 1 shows the components of LCOE of existing nuclear power plants projected by the International Energy Agency (IEA) in 2020 [6]. The discount rate is set at 7%. Information for IEA's LCOE projection are shown in Table I. As commonly recognized, the largest component of LCOE of nuclear power is the investment cost (also known as overnight cost) in all countries, unlike a fossil fuel plant where fuel price plays a crucial role. It is also noteworthy that in many Asian countries, the projected O&M cost occupies a significant share of LCOE in many Asian countries which might be due to the expenses for safety enhancement based on lessons learned from the accident at Fukushima Daiichi Nuclear Power Plant in March 2011. The projected fuel cost is generally low and is similar across the board, except for Russia. Finally, the decommissioning cost is projected to be very low as it arises at the end of the long life of a nuclear power plant. It is yet to be noted that decommissioning cost will be the largest portion of a nuclear power plant around the end of its life.

III.B. A single type of reactor helps streamline construction, operation, maintenance, and regulatory processes, leading to lower LCOE.

Taking a closer look at the two nuclear power leading countries, Japan and Korea, in Fig. 1. The proportions of each component of the projected LCOE of a similar advanced light water reactor (generation III+) are very similar (5:2:3:0). However, the total projected LCOE of Korea is significantly lower. The tighten regulatory requirements following the Fukushima accident, which could have been more consequential in Japan, may not be the only reason to this difference. While Korea has been focusing on APR-1400, which is an updated version of OPR-1000 in all its recent newbuilds, Japan has continued its programs on different types of advanced light water reactors. Focusing on a single type of reactor helps leverage efforts in technological advancement, optimization of operation and maintenance, and streamlining the regulatory process, potentially resulting in lower LCOE.

TABLE I. Information on nuclear power plants used for IEA's LCOE projection [6]

Country	Technology	Net capacity [MWe]	Efficiency [%]
France	EPR	1650	33%
Japan	ALWR	1152	33%
Korea	ALWR	1377	36%
Russia	VVER	1122	38%
Slovak Republic	Other	1004	32%
United States	LWR	1100	33%
China	LWR	950	33%
India	LWR	950	33%

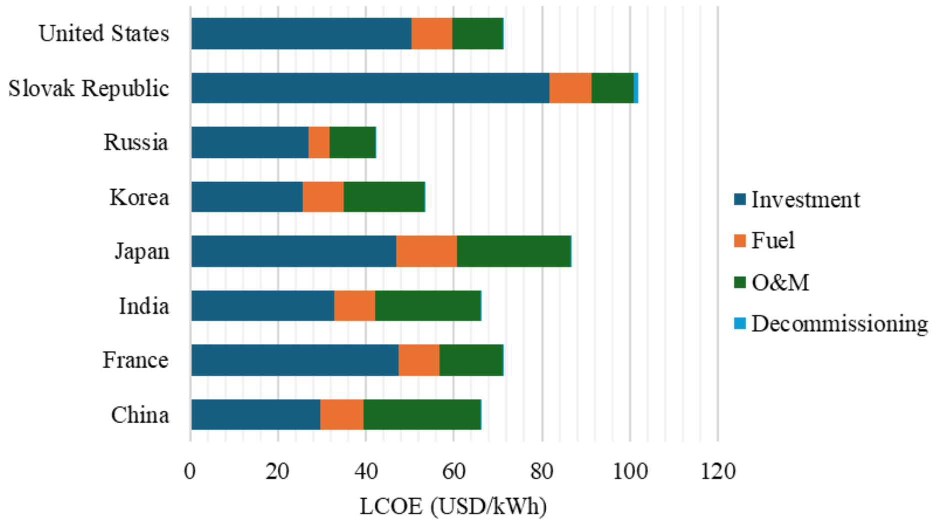

FIGURE 1. LCOE of existing nuclear power plants [6]

III.C. While material and labor costs are generally lower in developing nations, the LCOE is not necessarily always low depending on other circumstances.

Lower income countries tend to have lower material and labor costs compared to others. Russia is an exceptional case of a country with highly advanced nuclear power technology, but it still benefits from relatively low material and labor costs. As a result, the projected investment cost is low, and the projected fuel and O&M costs are exceptionally low. With a similar reason, the projected investment cost is also low for China and India. While there was a question on the correctness of the O&M cost data of China and India [7], the adjusted variable O&M cost of China at 15 cents per kWh is still higher than average. There might be other reasons for the high O&M cost which cannot be compensated for by the low labor cost.

III.D. A first-of-a-kind (FOAK) reactor tends to have a longer construction period and undergo longer inspections, resulting in a significantly higher LCOE.

Next is the case of France. While the Flamanville 3 EPR is theoretically not a first-of-a-kind (FOAK) reactor since its construction started after Olkiluoto 3 EPR, it can be practically considered as a FOAK plant as the two projects have only around two years' time lag. As it took nearly two decades (from December 2007 to September 2024) from the first concrete until the first criticality, the investment cost ballooned to nearly 70% of the projected LCOE. Note that the numbers in Figure 1 are the projected values based on the expectation in 2020 when the reactor was not yet in operation. It is highly likely that FOAK SMRs will follow a similar path with longer construction and inspection periods. It can be observed from the announced budget of Ontario Power's BWRX-300 where the first SMR is expected to be 7.7 billion CAD, and the total four units will cost up to 21 billion CAD [8].

III.E. Political stability is an important prerequisite for a lower LCOE while its impact is difficult to quantify.

The case of Slovak Republic also provides a good lesson to a newcomer regarding the influence of political situation. Czechoslovakia was separated into Czech Republic (currently Czechia) and Slovak Republic in 1992, and the construction of the nuclear power reactors was temporarily halted. The country also faces protests from the anti-nuclear neighboring country. While the impact from political instability can be observed from the projected overnight cost which becomes extremely high, it can only be quantified after the construction. While political risks are expected to be large, they are highly uncertain and will likely result in higher markups by vendors to compensate for the risks.

III.F. SMR in a newcomer country will always be more expensive, as it requires setting up legislative and regulatory frameworks and vendors will likely add markups to absorb their risks.

As SMR design requires multiple installations to maximize the economy of multiples, it is highly likely that many designs will involve export, with newcomer countries as their promising targets. For example, apart from its effort to promote VOYGR domestically, NuScale approaches foreign countries, including Romania which plans to deploy VOYGR-6 at Doicesti to replace a coal power plant [9]. However, statistics show that the same type of reactor will likely cost much more in the exported destination than in the original location. For example, the projected capital cost of an APR-1400 unit in Barakah Power Station is more than twice that in Saeul Power Station [3]. Apart from the costs for setting up the infrastructure based on the IAEA Milestones Approach [10], it is undeniable that the vendors should have added markups to cover the very large export risks. This may also be applicable to the case of BWRX-300 in Ontario [8] even if Canada is not a newcomer country as BWRX-300 will requires modification in regulatory requirements and additional infrastructure preparation.

III.G. While backend expenses are not typically included in LCOE, it may pose significant cost to the operator depending on the backend model employed.

Backend expense is not included in many LCOE calculations as there is no comparable component in other power sources. However, the cost to construct a final repository for spent nuclear fuel can be extremely high, and it will definitely affect the overall cost of an SMR project. There are also some other models for backend management, including spent fuel reprocessing and/or recycling abroad, a shared disposal facility, or a fuel leasing program [11]. All models require a significant amount of investment, and the country and the operator should be aware of it before making a commitment to a nuclear power program.

III.H. Initial estimates of LCOE are always much lower than the actual LCOEs.

Like other megaprojects, a nuclear power project is typically overbudget and delayed [12]. This is because it involves a high level of innovation and complexity, resulting in unexpected stumbling. IEA reported the statistics showing that the overnight cost of nuclear power projects can increase from 30% to three times of the initial estimation, and the construction period can be extended by 0.5 to three times. Emerging countries will need to be aware of the possibility of budget inflation and be prepared to deal with it.

III.I. While large reactors benefit from economy of scale, SMRs are expected to benefit from economy of multiples.

Economy of scale has been the very reason to continue enlarging the size of a nuclear reactor in the 90s and 2000s to reduce the unit cost [13]. On the other hand, despite the small size of SMRs which becomes a disadvantage in terms of scale, the economy of multiples with more opportunities to optimize, learn from the lessons, and shorten the construction time and regulatory process, multiple SMRs can be competitive to a single large reactor [14]. There is a high chance that a FOAK SMR will have a much higher LCOE than a typical large reactor, but the cost will likely reduce significantly for the second SMR and gradually decrease until it becomes relatively stable around the fifth SMR [15]. Therefore, it is advisable for a newcomer country to plan for a series of SMR construction of more than five reactors to sufficiently benefit from the economy of multiplication.

III.J. Good strategies are needed to enable the economy of multiples without losing SMR's benefit on financial risk.

With a significantly smaller capital cost per unit, an SMR is likely to have lower financial risk than a large reactor. It will be more affordable and have a shorter payback period. The modularity will allow the operator to benefit from scalability and design suitable portfolio strategy [16]. However, newcomer countries must note that the multi-module SMR may add up the total investment to be equivalent to that of a large reactor. While some SMR models allow gradual addition of SMRs, other models suggest deploying all modules at the same time. On one hand, multiple SMRs need to be installed to gain economy of multiples. On the other hand, deployment of SMRs needs to be carefully scheduled to distribute the investment in order to ensure low financial risk.

IV. CONCLUSIONS

Factors affecting the levelized cost of electricity (LCOE) of a small modular reactor (SMR) were identified and their tendencies when the SMR is deployed in a newcomer country are investigated and summarized below.

- The overnight cost is still generally the largest portion of the LCOE.
- Selecting a single model of SMR will lead to a lower LCOE when compared to multiple models.
- Developing nations may have lower LCOE as material and labor costs are lower, though it still depends on other circumstances.
- A first-of-a-kind (FOAK) SMR will yield a significantly higher LCOE.
- Political stability is an important factor affecting LCOE, though it is very difficult to quantify.
- Preparation of infrastructure and institutional frameworks, along with the high markups by the vendors will largely increase the LCOE of the first SMR in a newcomer country.
- All backend models require a significant budget, and its cost should be carefully considered before a newcomer country makes a commitment to an SMR program.
- Initial estimates of LCOE are always much lower than the actual LCOEs.
- The economy of multiples will compensate for the lack of economy of scale in SMRs, though it requires at least five SMRs for the impact to be significant.
- Strategies to distribute SMR investment are needed to benefit from economy of multiples through the deployment of multiple SMRs.

The findings show that there are many factors that will make the LCOE of an SMR higher than a conventional large reactor. A newcomer should plan for the deployment of a number of same type of SMRs with a carefully designed schedule. Rather than pushing forward with a FOAK SMR or an SMR model that has not been constructed elsewhere, a wait-and-see approach might be a wiser choice for a newcomer country with limited experience. For a developing nation, gradual localization will allow the country to benefit from lower material and labor costs and will also contribute to the advancement of domestic industry. To allow simultaneous deployment of multiple SMRs and enable regional approach to backend management, newcomer countries in an emerging region may consider negotiating SMR projects at a subregional scale.

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