การศึกษาศักยภาพของเครื่องปฏิกรณ์นิวเคลียร์ขนาดเล็กแบบโมดูล่าร์(SMR) เพื่อการพัฒนา: กรณีศึกษาประเทศไทย

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บทคัดย่อ

ในปัจจุบันหลายประเทศกำลังเผชิญปัญหาวิกฤตทางพลังงานและการเปลี่ยนแปลงสภาพภูมิอากาศอันเนื่องมาจากการปลดปล่อยก๊าซคาร์บอนไดออกไซด์ออกมาเป็นจำนวนเพิ่มมากขึ้น พลังงานนิวเคลียร์ซึ่งเป็นพลังงานสะอาด ราคาถูก และเป็นพลังงานที่ยั่งยืน จึงเป็นพลังงานทางเลือกอันหนึ่งที่ประเทศกำลังพัฒนาเลือกใช้เป็นพลังงานทางเลือกในปัจจุบันและอนาคต ในบทความนี้เป็นการรายงานผลการศึกษาของการนำเครื่องปฏิกรณ์นิวเคลียร์ขนาดเล็กแบบโมดูล่าร์ (Small modular reactor: SMR) มาใช้ในการพัฒนาและตอบโจทย์ปัญหาที่ประเทศกำลังพัฒนาเผชิญอยู่ จากการศึกษาพบว่า SMR เหมาะสมกับประเทศไทยในทุกด้าน โดยเฉพาะด้านการลงทุน เหมาะสมกับสายส่งไฟฟ้าของประเทศที่มีอยู่ มีความปลอดภัยสูงจากการออกแบบ และขนาดกำลังของการผลิตซึ่งสามารถเพิ่มขึ้นได้ สรุปได้ว่า SMR เหมาะสมกับการนำมาใช้เพื่อในประเทศที่กำลังพัฒนาโดยเฉพาะประเทศไทย

คำสำคัญ: พลังงานนิวเคลียร์; เครื่องปฏิกรณ์นิวเคลียร์ขนาดเล็กแบบโมดูล่าร์; ความได้เปรียบ; เปรียบเทียบกับเครื่องปฏิกรณ์นิวเคลียร์ขนาดใหญ่; ประเทศไทย

The Study of Potential Utilization of Small Modular Reactor (SMR) for Development : Thailand Case

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Abstract

According to present energy crisis in the world together with confronting to climate change due to increasing CO_2 emission, nuclear energy is considered as one of alternative sources of cheap, clean, and sustainable energy for base load electricity supply for industries. For small developing countries, such as Thailand with small capability of investment, together with small electrical grid system, small modular reactor (SMR) seems to be suitable for the country's economic growth and sustainable development. In this study, the prospect of utilization of SMR is examined in various aspects, i.e., general investment costs, suitability to the existing electrical grid matching, design simplification, and the nature of Nth- of-A-Kind (NOAK) of SMR, site selection, better safety by design, and integral scalability nature of the reactor. Those aspects are compared to large reactor (LR). It is found that SMR is more suitable to developing country as to Thailand case.

Keywords: **Nuclear Energy; Small Modular Reactor (SMR); Advantages; Comparison to Large Reactor; Thailand**

Introduction

At present, most countries around the world are facing with inevitable energy crisis, including Thailand. Due to previous decade of population growth, increasing price of fossil fuels, increasing demand of electric consumption on the average of 4.6% annually (Ministry of Energy, 2012), depletion of natural gas reserve in the gulf of Thailand within 10 years (at the present consumption rate), volatile situations in the middle east and the post Fukushima nuclear accident, the country has limited choices, but to seek for new, cheap, and clean alternative energy sources. Currently, electric generation of the country depends on 69.0 % of natural gas which about 33% is imported from Mynmar, 21% from coal and lignite, 4.0% from hydro, 0.7% from oil, 2.0% from Renewable energy, and 5.0% from purchased electricity from neighboring countries (Ministry of Energy, 2013) as shown in Figure 1.

As the consequence of Fukushima nuclear accident, the Thai government revised Power Development Plan to a new plan named PDP 2010 3rd revision (Ministry of Energy, 2012). In the new PDP plan, the energy plan is in a form of "energy mixed" in which nuclear energy, using large reactor (LR), is allotted to be 2,000 MW_e by the end of 2026. However, a new technology of nuclear reactor referred as "small modular reactor" (SMR) is recently introduced. Thus, it is a good opportunity for Thailand, the late "new comer" of NPP utilization, to compare and contrast between LR and SMR before making the decision to construct NPP in the country. Therefore, the feasibility study of using SMR in Thailand is urgently needed.

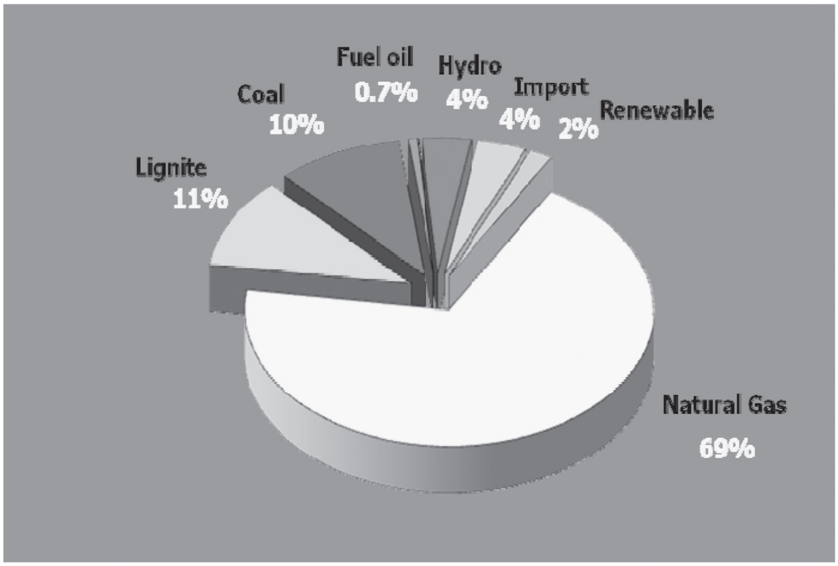

Figure 1 Share of power generation by fuel type January - March 2013 (Ministry of Energy, 2013).

Despite of SMR initiation by IAEA since 1985 (IAEA, 1985), it seemed that instead of most planners in nuclear energy would pay attention to SMR, however, they continue to cling on the concept of enlarging NPP size due to reduction of nuclear cost under the concept of "economy of scale" (EOS), rather than "economy of mass production" of small, integral, modular scalable unit of SMR. Recently, under IAEA guidance, energy crisis and lesson learned from Fukushima nuclear accident in 2011, SMR receives more attention in nuclear communities (Bhanthumnavin & Bhanthumnavin, 2011a, 2011b; Kessides, 2012), especially in USA and also in developing countries. The need of Thailand for alternative energy of cheap, clean, and sustainability is inevitable. One of alternative energy is nuclear energy with newly advanced technology of cheaper, simpler, safer : SMR (Vujic, 2012).

This study aims at reviewing the important issues and information of SMR, which will also include reactors of medium size (300-600 MWe) having the same technology as the small one of SMR. SMR in this study has properties of small/medium, modular, integral, scalable capacity unit. The advantages and disadvantages of SMR will be pointed out which will shade the light for making suitable decision to implement the first NPP in Thailand

Research Method

Data and information of this study are carried out through a process of gathering from articles in journals, conferences, reference sources i.e. technical reports and information from IAEA, NEA WNA as well as from SMR vendors' technical reports. These provide data of advantages and disadvantages for SMR and LR so that comparison between SMR and LR together with compatibility of utilization of SMR in developing countries can be concluded.

Hypothesis

It is anticipated that SMR will be suitable as alternative choice for utilization of nuclear energy in developing countries especially Thailand Case.

General Features of SMR

Small reactors has been utilized since the early 1950's with small capacity of power. Most of them were utilized for naval propulsion and as power sources in military bases. In USA, the first commercial NPP for electric power was operated at Shipping Port, Pennsylvania with power capacity of 60 MWe (Ingersoll, 2009: 591).

According to IAEA (1997; 2005), classification of reactors are classified into small, medium, and large ones as follow.

Small reactor is a reactor with the equivalent of electric power less than 300 MWe.

Medium reactor is a reactor with equivalent of electric power between 300 and 700 MWe.

For large reactor, it is considered as a reactor of typical equivalent electric power of 1,000 MWe or more. General data of small- medium reactors as given by IAEA (2010) are as followed.

- In-operation 133
- Underconstruction 12
- Number of countries with SMR 28
- Generating capacity (GWe) 60.3

Most of small reactors in NPP used pressurized water reactor (PWR) technology which has been proven for robust and reliable records. However, its structure and layout of the reactor was complicated and bulky in comparison to the new concept of the current small modular reactor, SMR. Figure 2 and 3

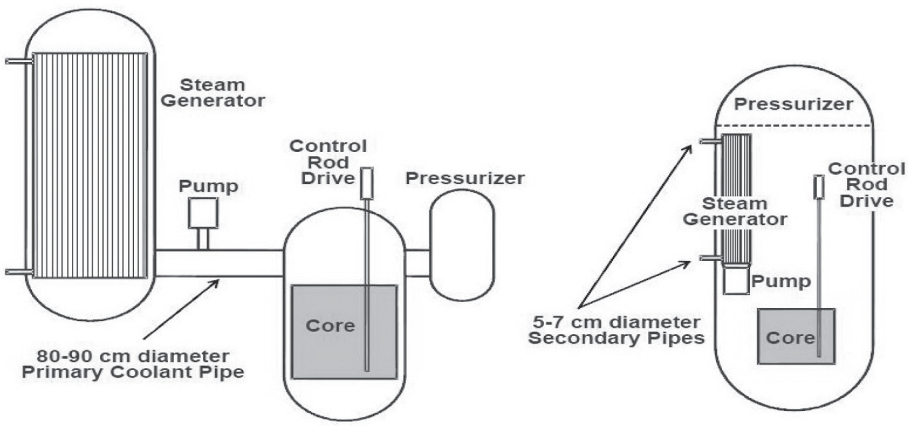

Figure 2 Comparison of large reactor (LR) size and small integral modular reactor (SMR) (Ingersoll, 2011a)

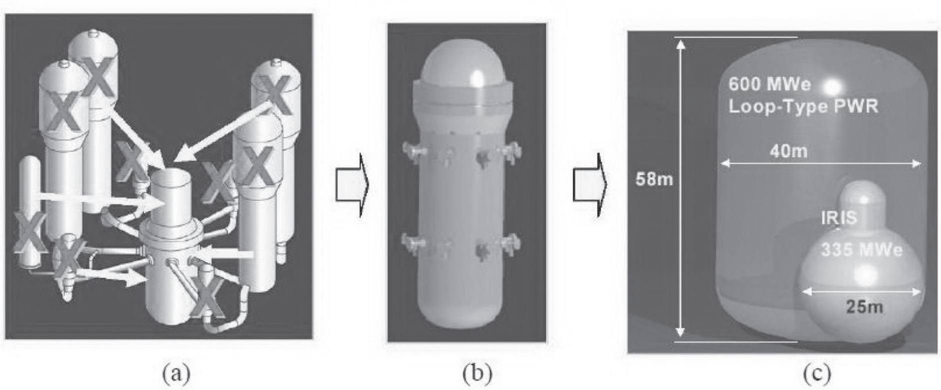

Figure 3 Comparison of LWRs with loop configuration (a) and integral primary circuit configuration (b), and the overall containment size (c) (Carelli, et al., 2005)

shows how the complication of reactor in the past has been reduced to very simple, robust, and more safety

SMR has advantageous characteristics of integral (where reactor core, steam generator, pressurizer, control roddrive, pipes are located and arranged inside single containment), modular (the reactor is a self contained unit whereby they can be set up in tandem for multiple scalable of needed power).

Results

Advantages of SMR

This paper is a part of feasibility study of potential utilization of SMR in Thailand. The major sources of information were from PDP plan 2010 3rd revision, technical documents from IAEA, NEA, OECD, as well as from articles in journals and technical document from SMR vendors.

SMR for electric generation and also for co- generation in Thailand was firstly introduced in 2010 (Bhanthumnavin & Bhanthumnavin, 2010). Since then, a great awareness of potential uses of SMR for development has begun (Bhanthumnavin & Bhanthumnavin, 2011a; 2011b; 2012). Authors have performed literature review in SMR, NPP public acceptance. From the study, a comparison of SMR to LR in 7 general important issues can be summarized as follows.

1. Reduce Investment Costs and Construction Time

If the country decides to choose LR for energy development then consequence of facing up with securing for a large amount of ever increasing financial investment in construction of LR with a high risk of construction delay time have to be met as happened to LR that its project is over budget and is many years behind schedule.

Since SMR is designed on the principle of small, integral, modular, and scalability, therefore, it will require relatively less amount of investment which is easily to get loan support in comparison to LR. Furthermore, construction time of the first unit of SMR is within 3 years, and a second unit can be added up later on (or concurrently constructed) (Figure 4). Therefore, the first unit can

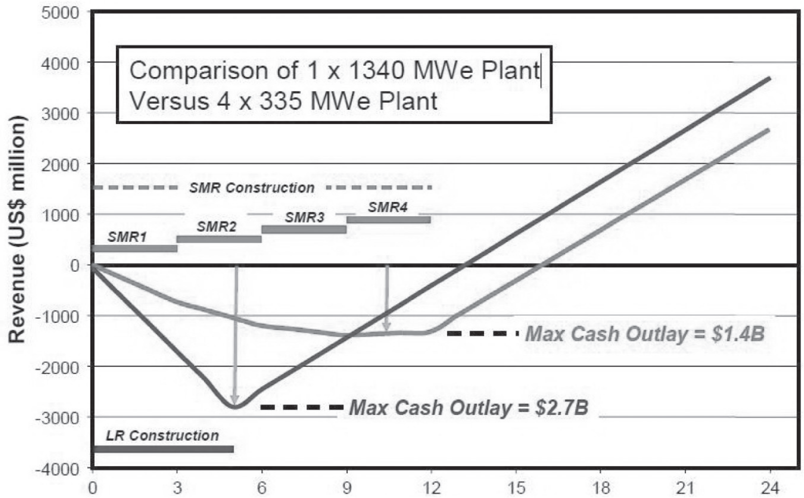

Figure 4 Staggered Build of SMRs Reduces Maximum Cash Outlay (Petrovic, 2010 cited in Ingersoll, 2011b)

generate electricity for income right away, not to wait for 10 years as LR case. From Figure 4, one can see that the maximum cash outlay of SMR construction is about 50% much less than the LR as follows.

Maximum cash outlay of SMR is $\frac{1.4 \times 10^9}{13.4 \times 10^5} = \text{US\$ } 1045 / \text{KWe}$

Maximum cash outlay of LR is $\frac{2.7 \times 10^9}{13.4 \times 10^6} = \text{US\$ } 2014 / \text{KWe}$

As to overnight cost consideration, at present the overnight cost of SMR is still varying. This is due to no SMR is in the commercial mode of operation yet. SMR's are in pilot operation stage and waiting for new license codes to be issued. It is anticipated that the codes will come out within two years. However, for the present overnight cost of SMR is about US$ 4,000/ KWe (WNA, 2013a). This figure has not included NOAK yet. For the case of LR, the overnight cost is about US$ 5,300-8,000 per KWe (Rogner, 2012; WNA, 2013b). Therefore, the overnight cost of SMR is slightly lower that LR by 24.53%

(without NOAK ofSMR). Therefore, is very suitable for nuclear energy development, especially for Thailand.

2. Better Power Plant and Grid Matching

SMR is more suitable to many countries since it can be matched to the existing grid of small and medium capacities (Carelli, et al., 2010). It is a high concern of establishing a new industrial park in the northeastern part of the country where few of electric generating plants with small grid existed./// With its property of small power generating capacity, SMR can fit nicely to the principle of distributed generation (Virginia Tech. 2007) in which small power generating units can provide electric power to community with short and small capacity of transmission lines. This aspect will save a lot of a cost of transmission line and also will reduce of transmission loss due to long distance in comparison to LR case. It will be effective to invest SMR for enhancing industrial development without much of investment in grid layout, and save electrical lost in transmission line due to long distance in comparison to LR.

3. Factory Fabrication, Mass Production Economy, and Lesson Learned Effects

Many nuclear scientists, engineers, as well as economists still believe in the classical law of "Economy of Scale" (EOS) which dictates the larger plant capacity for cheap electricity cost as indicated in (1).

$$\text{Cost}(P_1) = \text{Cost}(P_0)(P_1/P_0)^n \qquad (1)$$

where cost (P_1), cost (P_0) are costs of power plant for unit size P_1 and P_0 respectively, and n varies between 0.4 to 0.7 for the entire plant (NEA, 2011). For the case of SMR, EOS can be reduced by various factors, such as multiple units, learning curve, construction schedule, unit timing, and plant design as shown in Figure 5.

However, SMR does not follow (1) since it is entirely designed differently from LR. LR is designed and constructed as First-of-A-Kind (FOAK) with composing of many very complex systems, and constructed on site for one time only. However, SMR is produced on "Economy of Mass Production"-factory made. Due to its small size and integral unit in which major components, e.g., reactor core, steam generator, pressurizer, etc. are contained

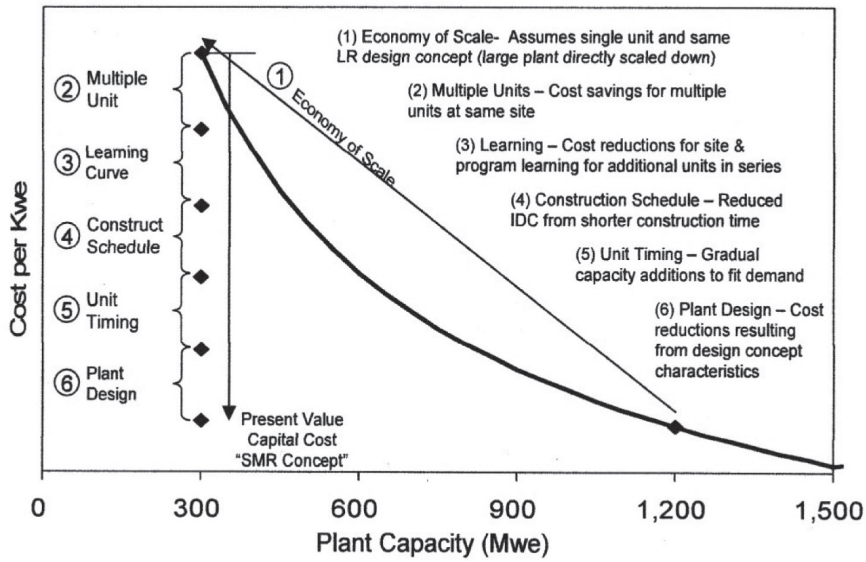

Figure 5 Factor affecting the competitiveness of SMR (Mycoff, 2007)

in small reactor vessel. Therefore it can be easily transported by truck, train, ship. It is more suitable for Thailand that an on-site construction which will demand more specialized workers, nuclear engineers, and special construction equipments. SMR is a product based on Nth-Of-A Kind (NOAK) as shown in Figure 6 like automobile where each modification, correction of the previous model will end up to be an improved and cheaper one (Mitenkov, et al., 2004).

4. Design Simplification

SMR has designed simplification in comparison to LR. It cuts down many redundant systems in LR (Carelli, et al., 2004) and by integral design of primary circuit, e.g., reactor core, steam generator, pressurizer, etc. are in the same containment with no large diameter piping that affectively eliminate the large break (in LR) lost of cooling accident (LOCA) (Ingersoll, 2011). These will be advantages for developing countries, like Thailand as to reduce risk on the technical safety of the NPP.

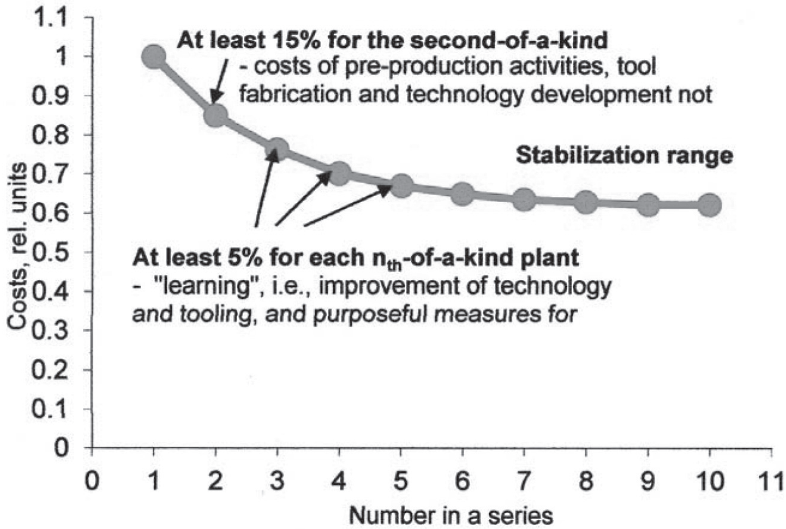

Figure 6 Reduction of equipment fabrication and installation costs in serial production of nuclear plant (Mitenkov, et al., 2004).

5. Site Selection

For SMR site selection, it is less complicated conditions in comparison to LR. Since SMR does not need a large water reservoir, e.g., lake, river, sea. It is not necessary to locate at the seashore (a risk of tsunami) or at the bank of the river (risk of flood). SMR does not need strong geological foundation as to LR. Therefore, site selection conditions are less for SMR. It can be on the remote area, dry land like the northeastern region, or mountainous terrains in the north and south of Thailand.

6. Better Safety

Safety aspect is a vital issue in relation to public concern. Past major nuclear accidents of Chernobyl, Three Mile Island, and recent Fukushima Daiichi, have created very much public concern of NPP. However, if one carefully considers the advancement of nuclear energy in SMR, the answer to the public concern in safety of NPP are given in SMR safety features in comparison to LR. Designs of SMR mitigate and potentially eliminate the need of back-up or emergency electrical generator.

Seismic capability of SMR has been improved tremendously due to the small size of the reactor vessel. Besides, the reactor vessel containment is in the pool of water and underground. This will dampen the effect of earth movement and enhance the ability to withstand earthquakes. Besides, there is "earthquake suppressor" unit attached directly to the reactor core due to its small size. This will improve an earthquake resistance tremendously.

SMR plants provide large and robust underground storage pool for the spent fuels. Thus, it is drastically reduced the potential of uncovering of the pool. So that spread out of spent fuel into atmosphere in case of accident will be reduced. SMR reactor vessel is underground. It reduces the chance of proliferation acts, and collision by commercial aircraft.

SMR inherits passive safety system which involves no external and internal electrical control circuits required. Also, there is no need for human interface. The passive system relies on natural physical laws, e.g., gravity, pressure, and property of materials, natural convection of air for decay heat removal in case of LOCA. These safety aspects mentioned above are in need and suitable for developing countries.

7. Spent fuel waste

Due to the small capacity, integral, modular, and scalable properties, SMR will yield small amount of spent fuel waste. Typical SMR has refueling time of 5 to 10 years and some types has life-long refueling time (no need to refueling). Therefore, it is save in dealing with nuclear waste. Besides, its fuel is contained in a sealed cartridge ready made from the factory. When the fuel is spent, the cartridge is taken out and sent back to the manufacturer. Therefore, the case of waste hazard and proliferation are avoided.

8. Caping Safety Hazards.

Due to small size with low power of reactor core and relatively large length-to-diameter ratio of the core, it will allow very slow and stable responses to transient caused by initiating events and for passive removal of decay heat in case of LOCA. These safety aspects are very much in needed for developing country where few experts and skilled technicians in nuclear field are scared to cope with in case of accident. Therefore, SMR is much more suitable compared to LR for Thailand case.

Comparison between SMR and LR

Summary of comparison between small modular reactor and large reactor is shown in table1 as flows:+

Table 1 Summary of Comparison between Small Modular Reactor (SMR of PWR technology) to Large Reactor (LR)

Aspects of comparison	SMR	LR
1. General Capacity and feature	It is a small capacity unit, power ranging from 0-300 MWe (small), 301-700 MWe (Medium) with new approach of integral, multiple, modular, scalable features (p 3, Figure 1 and 2) with weight about 500tons (including containment)	A large nuclear power plant (NPP) typically capacity of more than 1,000 MWe with complicated redundancy system of cooling piping, pumps, reactor core,
2. Technology and production process	Various of technologies. In this study SMR of PWR is considered because of long proven history of better. Safety in operation. Due to small integral unit production can be done easily and in a form of NOAK (rather than FOAK) i.e. factory made.	Various of technologies with good records of safety in operation. Due to heavy and complicated system, the production is only a form of FOAK and have to build/assembly in site and cannot be improved later on.

Table 1 (Continued)

Aspects of comparison	SMR	LR
3. Investment cost and construction time	- It is cheap due to they can be produce in mass (NOAK) and require small siting area, less components. The overnight cost is about US$ 4,000KWe (WNA, 2013a) - Constriction time is shorter (about 3 year/unit or multiple unit) since it has characteristics of integral, modular, scalability, etc. (See Figure 3 and 4)	- Due to large and heavy, the system required more investment cost not only the reactor system, but also siting area. Construction on site (not in the factory) needs more personnels for one time only (FOAK). Overnight cost is about US$ 5,300-8,000 per KWe (Rogner, 2012; WNA ,2013b) - Construction time is about (8 years including financial and site selection) or about 5 years if consider for construction only.
4. Better power plant and grid matching	SMR has properties that are suitable for local and industrial utilization. It can be fitted to the Distributed Generation (DG) system with matching to small grid capacity and proximity to the end user, leading to saving cost of long transmission line. SMR can response to current/future demand of power consumption due to it can be added (scalability) later (see section 3.2)	LR has large capacity of power generation (more than 1,000 MWe). Then it requires lager and longer transmission line to transmit power to the far away end user. It needs more investment for grid system unnecessary since LR sometimes provides more available power capacity available power capacity that takes many years before the increasing demand growth of consumption will match.

Table 1 (Continued)

Aspects of comparison	SMR	LR
5. Factory fabrication (Mass production)	Due to properties of SMR, especially small size and less complicated system, then SMR can be produced in the factory in many countries and the bring those parts to be assemble in the main factory. Aside, it can be considered as automobile production since SMR can be built as NOAK with better modification/ correction of later model (see Figure 4 and 5). This will reduce the cost of FOAK by about 30% after the 6th (NOAK). This suitable for developing countries.	Standard NPP (LR) is bulky withcomplicated redundancy system. It can be built only on site not in factories. Therefore, it is a FOAK product with economy of scale (EOS) approach. This will not only cost a lot of investment and operation /maintenance (OM) but also LR cannot be improved by using "learning curve" (See Figure 4 and 5). Investment and OM of LR require a lot of financial back up.
6. Design simplification	With lesson learned from Chernobyl, Three Mile Island (TMI), and recent Fukushima, SMR has been design and incorporated all lessons learned to its design so that it has more passive safety aspects and very ... of LOCA.	Due to dictation of EOS principal, LR has inevitably larger size with complicated system of cooling, piping, pumps which have more risks of accidents in comparison to SMR.

Table 1 (Continued)

Aspects of comparison	SMR	LR
7. Site selection	By design and its integral, modular scalability, safety, it does not require sophisticated cooling system as LR. It has less number of pumps and short and small diameter of pipe (about 5.0 centimeters). Therefore, it can be located in a remote, rugged terrain in dessert and no need of water resources at all. Since its weight is about 500 tons per module, therefore, no need of strong geological foundation at the site.	Since LR is huge and complicated system of old design, then it requires a large water resources in order to bring the water for cooling through a long and larger pipe (diameter of about 90 centimeters), need a high and tall cooling tower and more larger pumps. Therefore, site selection of LR is a major concerned. Normally LR will be situated near sea/ocean, rive, etc. it is suspected to tsunami and flood.
8. Better safety	SMR has better safety by design with lesson learned from previous accidents and operations of LR. Besides SMR with PWR technology which has proven records of safety in the submarine operation. The design for protection LOCA much better (see item 3.6) due to passive safety system. SMR is the Generation IV of reactor development. It has the	LR has also better safety aspect especially the current model of Generation III^+ with more passive safety system incorporated. Since LR has large capacity of more than 1,000 MWe, therefore the emergency planning zone (EZ) is about 16 km. (Carelli, 2008)

Table 1 (Continued)

Aspects of comparison	SMR	LR
8. Better safety (Cont.)	energy planning zone of 1.0 km only (Carelli, 2008)	
9. Caping safety hazard	SMR has small capacity. Therefore in case of accident when the reactor is shut down or stop the decay heat will be small amount about 70 MWh for the case of IRIS, and easily to be removed by the every effective passive removal by which no need of internal/ external of electricity. It seems that SMR (e.g., Nuscale) which is local in the underground pond. It can stand for decay heat removal for one month (ref). this is a very good answer to LOCA of Fukushima Daiichi Accident.	When LR is stopped, the decay heat will be large amount of about 210 MWh. It takes a lot of effort to remove it out in a week. Besides it needs electricity from internal/external to do so. Therefore, it ca not answer as to the case of LOCA situation like Fukushima Daiichi Accident.
10. Spent fuel waste	SMR produces small amount of spent fuel waste. For IRIS case, refueling time is about 5 years. Some types of SMR, there is no need for refueling and the fuel is contained in	Since LR is a large system of more than 1,000 MWe. It has a large amount of spent fuel waste and it is designed to have refueling tome period about 2 years. Therefore, in

Table 1 (Continued)

Aspects of comparison	SMR	LR
10. Spent fuel waste (Cont.)	a scaled cartridge and will be shipped back to a manufacturer in order to avoid hazard and proliferation.	refueling, the spent fuel will be taken out and keep at the NPP under water. This will take risk of being hazard and proliferation or in case of accident situation like Fukushima Daiichi case.

Challenges and Some Issues for SMR

In normal situation, evaluation of SMR for public utilization needs duration of 3-5 years in proven operating experience. However, SMR is still on the stage of application for commercial license. Furthermore, SMR location in remote area needs rigorous protection of higher degree of intrinsic reactor security. Management of nuclear fuel waste needs to be more international agreement, including mitigation of proliferation. Therefore, Thailand has to pay more attention to these issues for future nuclear energy development.

Recommendations

According to the literature review above, SMR has many advantages in comparison to LR. It can be concluded as a strong recommendation to Thailand PDP 2010 3rd revision of nuclear utilization. It is anticipated that nuclear energy in the part of "energy mixed" of 2,000 MWe by 2026, SMR will be a good choice for electric generation and co-generation rather than large nuclear reactor. Moreover, SMR can be utilized as a demonstration NPP for public education in Thailand.

It seems rather clear that SMR processes strong characteristics of integral, modular, scalability so that there is lower risk of accident in comparison to LR. As a consequence, the doubt of "safety" of SMR is not a major hindrance to the establishment SMR to be use as the first NPP in developing countries. The main hindrance of NPP establishment is in the area of knowledge of nuclear energy and trust in the government (Bhanthumnavin & Bhanthumnavin, 2012a). Therefore, the amalgamation of nuclear technology and behavioral science must be established an efforts to reduce these hindrances. One of solution to their problem is to innovation a new curriculum development called Nuclear Energy Management (NEM) curriculum in all levels in university (Bhanthumanvin & Bhanthumnavin, 2012b; ICTP, 2012). The NEM curriculum is offered for the first time in Thailand, in School of Management Technology (SoMT) at Shinawatra University (Bhanthumnavin, 2013) since September 2012.

To increase positive attitudes toward NPP, the government should start the first NPP project by using SMR in small contained areas, such as industrial parks in the north and northeastern parts of Thailand, or in military garrisons for energy security, as well for demonstration unit. Furthermore, utilization of nuclear energy for sustainable development leading to a low carbon society will need a special commitment from the government in every aspects so that it has to be concerned to various government agencies. For example, the Ministry of Energy and Environment, the Ministry of Education , the Ministry of Science, the Ministry of Public Health, the Ministry of Interior, the Ministry of Labor and Social Welfare , Office of the Prime Minister and etc. In other words it has to be “NATIONAL AGENDA” (Bhanthumnavin and Bhanthumnavin, 2012, p.28) in order to achieve to goal of utilization of the nuclear energy.

It is fortunate that Thailand still has a long period of time for preparation of a feasibility study of potential utilization of SMR before it can be utilized in 2026. With no hesitation, up-to-date information of SMR should be disseminated to public and concerned agencies for future PDP revision/preparation, and better public acceptance.

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