Examination of economics of small modular reactor based on overnight capital cost

Kim Phil Seo [a], Yim Man-Sung [a]
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701
Corresponding author: msyim@kaist.ac.kr

1. Introduction

Future energy demand will gradually increase, which is likely to increase demand for nuclear power also. Particularly in the fast-growing developing world, nuclear power is likely to be more essential in the future.

Therefore, in the future, it will be necessary for nuclear energy to be easily constructed and operated in a harsh environment where nuclear energy is needed by developing compact, transportable nuclear power. Many countries are currently developing small reactors, but they have not been commercialized yet. Therefore, it is important to evaluate the economic feasibility of the construction part of future small - sized nuclear reactors.

In this paper, we focus on Overnight Capital Cost (OCC). According to the NERA study, construction costs account for about 50-70% of the total capital of the reactor [3]. Therefore, the purpose of this study is to examine economics of small modular reactor based on overnight capital cost.

2. Methods and Results

2.1 What is Top-down?

The methodology of calculating the cost of generating electricity(LUEC) on nuclear power plant with small modular reactor is shown below[1].

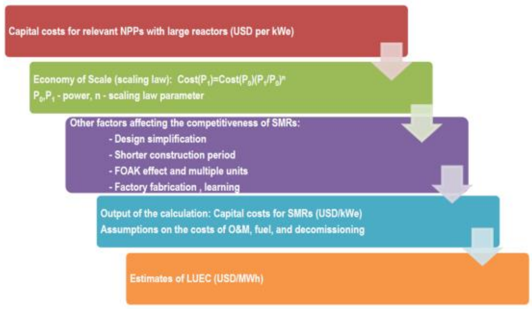


Figure 1 Methodology for independent LUEC estimates[1]

But actually, calculating shorter construction time is difficult. Therefore, the calculation of the interest rate due to the construction cost becomes also difficult.

So, in this section, only specific overnight capital cost is analyzed. Specific overnight capital cost is construction costs that do not take into account interest during construction and is the easiest to consider when considering nuclear power plant economic analysis.

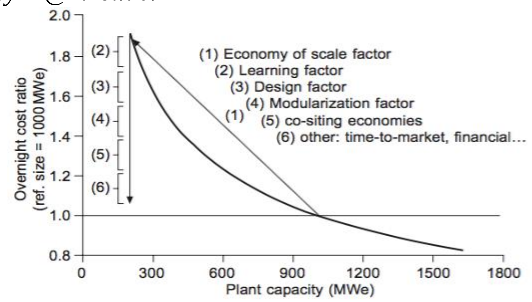


Figure 2 Top down basis

This figure show the method of calculating specific overnight capital cost. Cost estimation of SMRs is usually done by a top-down basis. Top down basis is started from available information on large, advanced pressurized water reactor (PWR) units, as a starting reference cost. And using various adjustment factors, we compare how expensive or costly a smaller reactor is than a commercial reactor.

Main factors that affect overnight capital cost of small modular reactors are; economy of scale, learning, modularization, co-siting etc.

2.2 Economy of Scale

The most important assumption when estimating the economy of scale factor is that it assumes that the small reactor and the standard large reactor are different in size and all components and designs are the same.

Then the specific overnight capital cost economy of scale equation is below.

$$\frac{Cost(P_1)}{P_1} = \frac{Cost(P_0)}{P_0}\left(\frac{P_1}{P_0}\right)^{n-1}$$

Here, there are various analysis results for the value of the constant n.

Table 1 constant n analysis

Carelli et al 2010 [1]	0.61
NEA / OECD 2011 [2]	0.51

For the need of the economy of scale factor especially for Korea case, information on the overnight capital cost of OPR-1000 and APR-1400 in Korea is shown below.

Table 2 Korea overnight capital cost

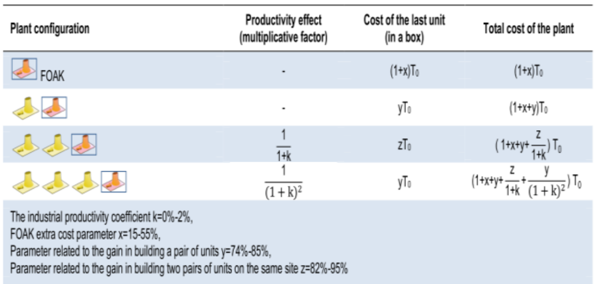
OPR-1000	1876USD/kWe
APR-1400	1556USD/kWe

And assigned to above equation, we could get constant ‘n’ for Korea case is 0.45.

2.3 Learning factor

In general, it is meaningful that the characteristic of the SMR is fabricated from the factory. Therefore, the more the production is made, the less the unit cost will be obtained through the ‘learning effect’. The factor that reduces the construction cost is called learning effect or learning factor. This learning effect factor differs greatly depending on whether it is First-Of-A-Kind (FOAK) or Nth-Of-A-Kind (NOAK).

NEA/OECD analyzed the learning factor from FOAK to NOAK through experiences in France[1].



Plant configuration	Productivity effect (multiplicative factor)	Cost of the last unit (in a box)	Total cost of the plant
FOAK	-	$(1+x)T_0$	$(1+x)T_0$
	-	yT_0	$(1+x+y)T_0$
	$\frac{1}{1+k}$	zT_0	$(1+x+y+\frac{z}{1+k})T_0$
	$\frac{1}{(1+k)^2}$	yT_0	$(1+x+y+\frac{z}{1+k}+\frac{y}{(1+k)^2})T_0$

The industrial productivity coefficient k=0%-2%,
FOAK extra cost parameter x=15-55%,
Parameter related to the gain in building a pair of units y=74%-85%,
Parameter related to the gain in building two pairs of units on the same site z=82%-95%

Figure 3 learning factor from FOAK to NOAK[1]

And for various modules scenario, the learning factor value is calculated below.

Table 3 Learning factor values for various modules

Modules	1	3	4	6
Learning factor value	1 1.35(FOAK)	0.90	0.87	0.75

2.4 Modularization factor

It should be noted here that the assumptions made when using the economy of scale factor are that the small and the large reactors is different in size but same for other options. But small modular reactors are very different in design from large reactors. So the modularization factor is taken into account. This modularization factor represents a cost savings due to the design of small reactors.

Of course, it is difficult to obtain the modularization factor of each kind of small reactor, but there is a graph in which Reid makes approximate estimation (Reid 2003). Reid has developed a graph that estimates the modular adjustment factors from 35 MWe to 600 MWe [5].

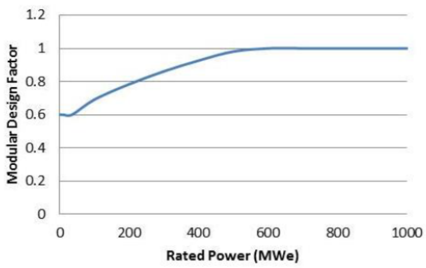


Figure 4 modularization factor[5]

Also, the modularization factor equation is below.

$$4\times10^{-10}(P_r)^3-10^{-6}(P_r)^2+0.0012(P_r)+0.581[5]$$

And using this equation, the modularization factor for various rated power scenario is below.

Table 4 Modularization factor for various power

Power(SMR)	Modularization factor
100MWe	0.69
150MWe	0.74
200MWe	0.78
250MWe	0.82
300MWe	0.83

2.5 Co-siting factor

If there are several reactors in one site, there will be occasions when they share the same facility or some manpower. And this occasion can lead to reduce the cost. This cost reduction is called the site co-siting factor.

The IAEA report gives a graph of the co-siting economy factor. [6]

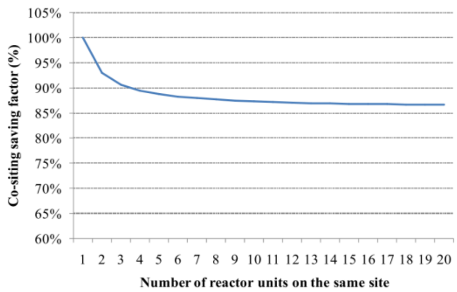


Figure 5 Co-siting factor[6]

In the case of small reactors, since the output per reactor is small, it is possible to obtain a desired output value by constructing many small modular reactors in one site rather than constructing one large reactor with same total power. Therefore, when several modules are installed, they could share the fixed capital. Thus, if many small reactors are installed in one single site, the average cost of capital per small reactor will decrease.

Using the above graph, the estimation of co-siting factor value could be obtained approximately.

Table 5 Co-siting factor value for various modules

Modules	1	3	4	6
Co-siting factor value	1	0.90	0.89	0.88

2.6 Other factors

There are some other factors that influence the top-down basis analysis.

- Contingency
- Construction duration

2.6 How factors can influence overnight capital cost?

1. *negative influence*

   The main factor that negatively affects the specific capital cost is the economy of scale. [1] As small modular reactor power is low compared with large reactor. So the specific capital cost would be much higher than large reactors in the unit of [USD/kWe].

2. *Positive influence*

   Because small modular reactor can be fabricated and manufactured fully in factory [1], the learning factor would be positively influence the OCC. For the same reason, construction time also has a positive effect because of factory fabricated.

   Modularization, also called design simplification will reduce OCC because of integrated model.

2.7 Economic assessment of various module scenarios

This top-down method is used to analyze how the output and the number of modules will affect the total output power. Assuming 1200MWe at total output, we divide into three cases as follows

① 200MWe -6 modules
② 300MWe – 4 modules
③ 400MWe – 3modules

The APR-1400 large reactor overnight capital cost was selected as the reference cost. Using top – down basis analysis, assessment of economics of various scenarios is shown below.

Table 6 Assessment of economic of SMR with various modules scenarios

Power/module	200Mwe*6	300Mwe*4	400Mwe*3
Scaling factor	$(\frac{200}{1343})^{0.45-1}$ = 2.85	$(\frac{300}{1343})^{0.45-1}$ =2.28	$(\frac{400}{1343})^{0.45-1}$ =1.94
Modular Design	0.78	0.86	0.92
Learning	0.75	0.87	0.90
Co-siting	0.88	0.89	0.90
Total	1.46	1.65	1.45

As a result of analysis, when the total power demand is the same, the most feasible option is 400MWe with 3 modules.

3. Future Work

In fact, it is not appropriate to conduct economic analysis only with overnight capital cost. It is necessary to analyze various economics such as operation maintenance cost, dismantling and decontamination cost, nuclear cycle cost, etc.

Therefore, in future research, these various factors are to be analyzed to make the economic analysis more accurate.

REFERENCES

[1] "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors," NEA/OECD, 2011

[2] M. Carelli, P. Garrone, G. Locatelli, M. Mancini, M. Mycoff and P. Trucco, "Economic features of integral, modular, small-to-medium size reactors," Progress in Nuclear Energy, vol. 52, pp. 403-414, 2010

[3]Mackerron G., Colenutt D., Spackman M, Robinson A., Linton E., "Paper 4: The economics of nuclear power, report for the Sustainable Development Commission by Science & Technology Policy Research (SPRU, University of Sussex) and NERA Economic Consulting, March 2006

[4] L.M. Boldon, P. Sabharwall, Small Modular Reactor : First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis Idaho National Laboratory Summer 2014 Report, (2014).

[5] L. Reid, "Modelling Modularity Impacts on Nuclear Power Plant Costs," Oak Ridge National Laboratory, 2003

[6] IAEA, Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors, Nucl. Energy Ser. NP-T-3.7 (2013).