Economic Assessment of SMART Deployment in Korea using DEEP 5.1

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1. Introduction

Small Modular Reactor (SMR) is of interest because of its potential capability to supply grid-appropriate electricity and by-product such as desalinated water or heat depending upon customers' needs. A bright prospect of SMR market in the future has led System-integrated Modular Advanced Reactor (SMART) to be developed by Korea. SMART is designed to produce 330MW thermal energy and 40,000m^3/day desalinated water with enhanced safety system. The design acquired the standard design certification from Nuclear Safety and Security Commission (NSSC) for the first time in the world. Nonetheless, SMART is estimated to have a higher cost of energy compared to other power sources, so investors were restrained from ploughing their asset into construction of the first unit as a demonstration plant. Such a dismal economic outlook discouraged Korean nuclear power industry and potential purchasers from deploying SMART. In this study, economic assessments were conducted to figure out economic competitiveness of SMART. Desalination Economics Evaluation Program (DEEP) software which was developed and distributed by International Atomic Energy Agency (IAEA) was used to analyze the cost of electricity and water of SMART and other power plants.

2. Methodology

2.1. SMART design overview

SMART is an integral-type reactor that houses reactor coolant system and main components in one pressure vessel which are connected without pipes. Nuclear fuel, reactor core, eight steam generators, one pressurizer and four reactor coolant pumps are equipped in a unitary reactor pressure vessel. Highly advanced design features to enhance the safety, reliability, performance and operability are applied to the SMART design. In particular, incorporated inherent safety improvement features and reliable passive safety systems were introduced to achieve the safety and reliability goal. [1]

2.2. Basic concepts of plant economics

Two concepts of plant economics were used in this study, Levelized cost of electricity (LCOE) and overnight cost. LCOE is a yardstick for measuring economic feasibility of power sources. It can compare economics of power plants that have different lifetime and different type of fuel in a reasonable manner. It is calculated by dividing total cost to build, operate and decommission plant by net power output during its whole lifetime. The unit of LCOE typically used is $/MWh.

Overnight cost is another commonly used concept representing the cost of constructing plant assuming no interest occurred during its construction period. The terminology "overnight" originated from its meaning that it means the cost of completing plant construction overnight. [2]

2.3. Desalination Methods.

Technologies currently used for desalination are divided into two types: distillation process and membrane process. Distillation process produces fresh water using flashing and evaporation. Membrane process is a water purification technology that uses a semipermeable membrane to remove larger particles from drinking water. In the world market, countries that need large scale desalination facility usually have chosen distillation process such as Multi-stage flash (MSF) or multi effect distillation (MED), whereas other countries who do not need large capacity have chosen membrane process like reverse osmosis (RO) process. For this study, hybrid process which is a combination of distillation process and membrane process was used to assess the economic feasibility of desalination plant.

2.4. Desalination Economics Evaluation Program (DEEP)

To evaluate economics of SMART and concomitant desalination facility, this study used DEEP software. DEEP allows designers and decision makers to compare economics of various desalination and power configurations. For this study, this software was used to derive electricity generation cost and desalinated-water production cost of SMART and other competing power sources. [3]

3. Economic Evaluation of SMART

3.1. Input parameters

First-of-a-kind (FOAK) unit of SMART has not been built yet, therefore it is almost impossible to precisely estimate the construction cost. From its technical design, the target overnight construction cost (OCC) was assumed to be 5,000$/kWe. Due to the uncertainty, various overnight costs varying from 4,500$/kWe to 15,000$/kWe were assumed for calculation. The minimum overnight cost was derived using scaling factor, and the formula is as below.

$$\mathrm{OCC}_{\mathrm{SMR}} = \mathrm{OCC}_{\mathrm{LARGE}} \times \left(\frac{size_{SMR}}{size_{LARGE}}\right)^{n-1} \quad (1)$$

, where n is the scaling factor.

Applying scaling factor, 0.62, and the overnight cost of OPR-1000, overnight cost of SMART was computed to be 4,500 $/kWe. The maximum overnight cost was assumed to be three times of the target cost, which is 15,000 $/kWe.

Since this study is based on an assumption of deploying SMART in Korea, the real fuel price in Korea was used for estimation. According to electric power statistics information system (EPSIS) operated by Korea Power Exchange (KPX), the current fuel price for nuclear power plant, 4.47 $/MWh, was used for the fuel price. Fuel escalation ratio was calculated to be 3.34% per year, which is the average annual fuel price escalation during the past fourteen years.

Operation and maintenance (O&M) cost was quoted from technical design of SMART. Data for desalination related parameters reflect real data in Korea. The seawater total dissolved solid (TDS) value was selected from the measured data in the East Sea. The average seawater temperature near to Je-ju Island was used for the input, as well.

Other parameters and their input values are described in Table 1.

Table 1 Input parameters for economic assessment

Parameters	Value	Unit
Basic Economic Parameters		
Lifetime	60	years
Currency rate	1,160	KRW/USD
Discount rate	6	%
Interest rate	5	%
Technical Parameters		
Construction cost	4,500~15,000	$/kWe
Construction period	36	months
Auxiliary load	5	%
Capacity factor	90	%
Fuel cost	4.47	$/MWh
Fuel cost escalation	3.34	%
O&M cost	6.81	$/MWh
Desalination Data		
Desalination capacity	40,000	m^3/day
Water salinity (TDS)	34,090	ppm
Seawater temperature	18	℃
Thermal/RO ratio	50	%

3.2. Result

In order to assess power and water cost according to the various overnight cost, the output was calculated using different overnight costs. Interestingly, the power cost, cost of generating electricity, was almost proportional to the overnight construction cost. This implies that the overnight cost determines power cost rather than O&M cost or fuel cost, therefore reduction of construction cost can be regarded as a key factor for the successful deployment of SMART. The detailed result of simulation is illustrated in Table 2.

Table 2 Result of DEEP Calculation

Overnight Cost [$/kWe]	Power Cost [$/MWh]	Water Cost [$/$m^3$]
4,500	71.9	0.94
5,000	78.1	0.97
6,000	90.6	1.03
7,000	103.1	1.09
8,000	115.6	1.15
9,000	128	1.21
10,000	140.5	1.27
11,000	153	1.32
12,000	165.4	1.38
13,000	177.9	1.44
14,000	190.4	1.5
15,000	202.9	1.56

4. Economic Evaluation of SMART Deployment in Remote Area

SMART is far from exploiting the economics of scale in a centralized electricity grid system. SMART has more advantages when it is built in remote area where small-medium capacity of electricity is in need or where the cost of connecting to the central electricity grid is too expensive. For this study, to figure out the economic value of deploying SMART in remote areas, a case study was conducted. This case study estimated the economics of constructing a high voltage direct current (HVDC) line to receive electricity from remote central electricity grid. In this case, net electricity cost using HVDC transmission is as below:

$$\begin{aligned} &\text{Net cost of electricity using HVDC transmission} \\ &= (\text{average unit cost of purchasing electricity}) \\ &\quad + (\text{levelized cost of electricity transmission}) \quad (2) \end{aligned}$$

The average unit cost of purchasing electricity is the cost KPX pays to purchase electricity and it turned out to be 65.98 $/MWh for inland case. To figure out the cost of HVDC transmission system, empirical data of "Jeju~Jindo" line was used. Table 3 describes input data used for this calculation.

Table 3 Input parameters regarding HVDC

Parameter	Unit	Value
Capacity	MW	200
Number of lines	EA	2
Length	km	120
Construction cost	billion KRW	618.5
Construction period	year	3
Lifetime	year	40
Annual O&M cost	million KRW	1,546

Currency rate	KRW/USD	1,160
Interest rate	%	5
Loss of electricity	%	3

It is necessary here to derive a new formula to calculate the levelized cost of transmission system. In this study simplified levelized cost of electricity (SLCOE) formula was converted to calculate the levelized cost of electricity transmission as below.

$$\text{SLCOE } [\$/\text{MWh}] = \left\{\frac{(\text{overnight capital cost} \times \text{CRF}) + \text{fixed O\&M cost}}{8{,}760 \times \text{capacity factor}}\right\} + \text{fuel cost} \times \text{heat rate} + \text{variable O\&M cost} \quad (3)$$

$$\text{where, CRF (Capital Recovery Factor)} = \frac{i \times (1-i)^n}{(1+i)^n - 1}$$

i=interest rate
n=number of annuities receive

The unit of overnight capital cost, fixed O&M cost, and variable O&M cost are $/kWe, $/kW-year, and $/kWh, respectively. Simplified levelized cost of electricity transmission (SLCOET) can be devised by eliminating parameters such as capacity factor, fuel cost, heat rate, and variable O&M cost that have no relation with transmission system.

$$\text{SLCOET (simplified levelized cost of electricity transmission)} = \left\{\frac{(\text{overnight capatica cost} \times \text{CRF}) + \text{fixed O\&M cost}}{8{,}760}\right\} \quad (4)$$

The table below illustrates the result of calculation and comparison with the levelized cost of SMART. Compared to the levelized cost of HVDC transmission, SMART is encouraged to be built with an overnight cost less than 5,000 ~ 6,000 $/kW. This result is not quite optimistic, however comparing the unit cost of purchasing electricity in Je-ju Island, 150.98 $/MWh, SMART can have economic competitiveness as a small-medium size electricity supplier. Economic assessment of SMART compared to the alternative power sources that can be built in remote areas was conducted in the following chapter. [4]

Table 4 Result of HVDC economics calculation

OCC of SMART [$/kWe]	Power Cost of SMART [$/MWh]	Net Levelized Cost using HVDC transmission [$/MWh]				
		40km	80km	120km	160km	200km
4,500	71.9					
5,000	78.1	74.28				
6,000	90.6		80.32	86.78		
7,000	103.1				92.62	98.77
8,000	115.6					
9,000	128					
10,000	140.5					

5. Economic Comparison with Alternative Power Sources

The purpose of this chapter is to determine economic competitiveness of SMART compared to the other alternative power sources. The other alternatives mean other power plants that are adequate to be built in remote area where electricity grid capacity is not huge. The input parameters and its values are described in the table below. For each of the power sources, carbon capture and storage (CCS) technology implemented plant was additionally considered to compare the low carbon emitting plant with SMART.

Table 5 Input parameters of alternative plants

Parameter	Unit	Coal		Gas	
		Advanced PC*	Advanced PC with CCS	Advanced CC**	Advanced CC with CCS
Capacity	MWe	650	650	400	340
Overnight capital cost	$/kW	3,246	5,227	1,023	2,095
Fixed O&M cost	$/kw-yr	37.8	80.53	15.37	31.79
Variable O&M cost	$/MWh	4.47	9.51	3.27	6.78
Fuel price	$/ton $/mmBTU	75.45	75.45	11.13	11.13
Fuel price escalation	%	5.79	5.79	3.56	3.56

* PC : Pulverized Coal, ** CC : Combined Cycle

The fuel price was quoted from EPSIS and fuel price escalation was calculated for the past fourteen years. Other input parameters and their values are as below: (1) Construction Period; 24 months, (2) economic lifetime; 30 years, (3) capacity factor; 85%, (4) desalination capacity; 100,000 m^3/day. The economic evaluation of alternative plants was conducted using DEEP software, and the result obtained is shown in Table 6.

Table 6 Result of alternative plants economic analysis

OCC of SMART [$/kWe]	Power Cost of SMART [$/MWh]	Coal Plant Power Cost[$/MWh]		Gas Plant Power Cost [$/MWh]	
		Advanced PC	Advanced PC with CCS	Advanced CC	Advanced CC with CCS
4,500	71.9				
5,000	78.1				
6,000	90.6				
7,000	103.1				
8,000	115.6				
9,000	128	118.6			
10,000	140.5			132.7	
11,000	153				151.9
12,000	165.4		162		
13,000	177.9				
14,000	190.4				
15,000	202.9				

The result of this calculation was somewhat encouraging that SMART can have a competitiveness with 9,000 $/kWe overnight cost over advanced coal power plant and gas turbine plant. Also, comparing plants with CCS facility, the target cost to build SMART increases to 11,000 $/kWe. In the paragraph that follows, the effect of carbon tax on fossil power plants without CCS equipment and following re-evaluation of economic feasibility will be discussed.

In recent years, concerns about environment have urged to legislate carbon tax on greenhouse gas emission. Korea has been circumspect on carbon tax, but in the near future the carbon tax can be imposed to power plants. Economic feasibility of SMART and other alternative plants was assessed presuming carbon tax to be imposed. Table 7 describes the result of this assessment.

Table 7 Result of calculation considering carbon tax

Overnight Cost [$/kWe]	Carbon Tax : 30 [$/ton]		
	Power Cost of SMART [$/MWh]	Advanced PC [$/MWh]	Advanced CC [$/MWh]
4,500	73.4		
5,000	79.7		
6,000	92.3		
7,000	104.9		
8,000	117.5		
9,000	130.1		
10,000	142.7		
11,000	155.3	152.2	144.7
12,000	167.9		
13,000	180.5		
14,000	193.1		
15,000	205.7		

Table 7 describes the result of calculation considering carbon tax. Assuming carbon tax of 30$/ton, power cost of other alternative power plant who does not equip CCS facility increases. This result gives SMART more economic competitiveness, that 10,000~11,000 $/kWe of overnight cost can be allowed. If the carbon tax increases to be 50 $/ton, the power cost becomes 186.7 $/MWh for advanced PC plant, and 152.7$/MWh for advanced CC plant. Overall, these results indicate that anticipated carbon tax gives SMART advantage on economic aspect. [5]

6. Conclusion

This study set out to evaluate the economic competitiveness of deploying SMART in Korea. The levelized cost of energy of SMART was derived using DEEP software. As overnight construction cost increases from 4,500 $/kWe to 15,000 $/kWe, levelized cost of electricity proportionally rises from 71.9 $/MWh to 202.9 $/MWh. This implies that controlling overnight construction cost is a key factor of the economic competiveness of SMART.

SMART is appropriate for small-medium sized remote electricity demand, so a related case study was conducted. To compare with cost of SMART deployment, the cost of connecting electricity grid using long HVDC transmission line was calculated. The cost of HDVC transmission line construction and operation varies depending upon its length and capacity. In case of 120km HVDC transmission system, 5,000 $/kWe overnight cost of SMART can have competiveness.

A comparison of economic value between SMART and other alternative power sources were conducted using DEEP software. The alternative power sources were coal power plant and combined cycle gas turbine plant. Assuming those power plants generates certain amount of water to be fairly compared with SMART, DEEP software calculated SMART should be built with maximum 9,000~10,000 $/kWe construction cost. Compared to the plants with CCS facility, allowance of SMART construction cost increases to be 11,000~12,000 $/kWe.

Another assumption was considered to highlight the merit of SMART which emits almost zero carbon compounds. Applying carbon tax to the previous study, LCOE of SMART and other power sources was calculated. The result shows that overnight construction cost of SMART can be increased to be 11,000 ~ 12,000 $/kWe.

These results can encourage decision makers to deploy FOAK unit of SMART in Korea. However, further studies are needed because feasibility of SMART deployment in Korea still remains uncertain. Public opinion, suitable footprint issue, and regulation rigidity are those obstacles to overcome. Careful concern over policies and strategies for SMART deployment shall be required from now on.

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