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Deterministic Cost Estimate of EU-APR

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1. Introduction

EU-APR has been developed based on the design of APR1400, and the European requirement on the PWR plant design was considered thoroughly. While the EU-APR design adopts the up-to-date safety features, the design optimization was also considered in the economic aspect. The factors that have effect on the future owner's project feasibility and profitability such as total project cost, constructability, construction time, licensing and other various factors were also considered for the design optimization so as to minimize the owner's capital investment and lifecycle cost and better achieve the project implementation. This evaluation utilizes levelized cost approach as a measure of economic feasibility and a way of accessing the design optimization.

The cost analysis has mainly focused on the design changes of EU-APR compared to APR1400 design and consequential changes in economic aspect. EU-APR has the following additional design features regarding the safety-related issues;

Technical characteristics and design features stated above were considered to make cost estimate. Differences on quantity and price compared to APR1400, which provides basis for cost estimate with construction experiences in Korea, were analyzed for the capital cost estimate of EU-APR.

It is important to recognize that the following assumptions underlie this report to analyze the technical and economic differences of EU-APR. First, construction and operation of EU-APR is assumed to be performed at the new sites in Korea under the same conditions as Korean commercial nuclear reactors generally have. As construction and operation costs of a type of plant can be varied according to the country or location, the assumption is required to reasonably compare EU-APR to APR1400. Thus, the project environment of EU-APR in this study, covering factors of cost estimate such as equipment purchasing cost and construction labor cost, should apply the environment of Korean nuclear power plants. However it is also important to note that most of the technical characteristics and design features are to be complying with the design for European construction though EU-APR is assumed to be built in Korea. Second, to calculate generation cost of EU-APR, the adoption of the standard practice of Korea, such as account of capital cost and method of calculating levelized cost, is required in accordance with the first assumption. Therefore, standard practice of KHNP is applied to correctly evaluate the economic aspect of EU-APR compared to APR1400.

2. Parameters for Cost Estimate

A set of input parameters for the cost estimate is given as follow. This economic evaluation carried out analysis with conditions of constant price at January 1 of 2016, discount rate of 3.71%, debt ratio of 100%, and capacity factor of 85%.

Table 1. Cost Estimate parameters of EU-APR

items	Cost Estimate Parameters
Base date(reference date)	2016.01.01
Plant output (gross)	1,455MWe
Auxiliary power rate	4.1%
Plant economic life (design life of the plant)	60 years
Plant availability factor	92%
Plant capacity factor	85%
Discount rate	3.71%/year
Interest rate	3.71%/year
Portion of loan to total capital	100%
Currency exchange rate	1,100KRW/USD, 1,350KRW/EUR, 10KRW/JPY
Depreciation method	Straight line method (residual value 0%)
Nuclear power R&D fund payment	1.2KRW/kWh (included in O&M cost)

3. Design Features of EU-APR

EU-APR has the following additional design features regarding the safety-related issues. Additional redundancy for the important safety functions is provided to improve the reliability and to enable on-line maintenances. Diverse measures for reactor shutdown and emergency power supply against the failure of front systems performing the allocated safety functions. Aircraft crash hazard is taken into account in the EU-APR design so that the leak tightness of the primary containment is maintained and the safety-related systems are protected by the secondary containment wall and the Auxiliary Building (AB) exterior wall and roof. SA (Severe Accident) mitigation systems, such as

Passive Ex-vessel corium retaining and Cooling System (PECS) and Containment Filtered Vent System (CFVS), which are independent of the systems for normal operations or postulated accidents, are provided to ensure the containment integrity in the event of SA. The rated frequency of 50 Hz is adopted for all AC electrical systems in the EU-APR. The design of electrical and I&C systems is in accordance with international codes and standards such as IEC. Design improvements to reduce radiological releases during normal and postulated accident conditions are made.

Table 2. Summary of EU-APR design features

	Item	EU-APR	APR1400
1	Containment Integrity	Aircraft impact Design	-
2	Seismic design	0.25g	0.3g
3	RX Building Type	Double Containment	Single Containment
4	Reactor Building entrance and exit during Normal Operation	Permission	Restriction
5	TBCCW HX	TBN BLDG Inside	TBN BLDG Outside
6	EDG	4 /unit	2/unit
7	AAC	2/unit (Gas TBN)	2/unit (Diesel)
8	Electrical Frequency(Hz)	50	60
9	Safety System	4 Train	Semi-4-Train
10	Molten Core Cooling System	Core-catcher	CFS※ IVR-ERVC

※ CFS : Cavity Flooding System
IVR-ERVC : In-Vessel Retention –External Reactor Vessel Cooling

4. Cost Estimate Methods and Results

KHNP's guideline of calculating LCOE(Levelizing Cost Of Electricity) refers to the Economic Evaluation Guidelines of Nuclear Power Plant which was published by KHNP in 2008. In the general method LCOE is calculated by levelizing annual irregular costs and generation amount on yearly basis considering time value of money, however, this method simplifies the way of calculating LCOE in some points. While extensive consideration for the distribution of costs over time is needed for LCOE calculation in the general method, KHNP's guideline uses expected average costs in some operating expenditures.

4.1 Capital Cost

Capital investment cost is reflected into LCOE by using fixed charge rate which considers capital recovery factor and corporate tax rate.

Fixed charge rate = Capital recovery factor + Corporate tax factor

$$\text{Capital recovery factor} = \frac{i(1+i)^N}{(1+i)^N - 1}$$

i : discount rate, N: plant life

$$\text{Corporate tax factor} = \frac{Y}{1-Y} \times (C \times FC) \times [1 - \{(N-1) \times D \div 2\}] \times 100$$

Y : Corporate tax rate (residence tax included)
N : Useful life of asset (economic life time)
C : Expected annual revenue to investment capital (discount rate is commonly used as an alternative)
FC : the ratio of owner's equity to the total capital (the ratio of owner's equity). 50% is generally used
D : Depreciation rate (straight-line method)

Capital recovery factor is used to retrieve invested capital in levelized amount of money during project period considering time value of money, and corporate tax rate is used to apply corporate tax that has to be spent in proportionate to operating profit. When corporate tax is considered as a cost element, it is included in O&M cost for the general method, however, it is calculated within the capital cost here for easier prediction of the cost. The capital cost in LCOE is calculated as below.

Capital cost in LCOE

$$= \frac{\textit{total capital investment cost} \times \textit{fixed charge rate}}{\textit{plant gross output}(kW) \times 365 \times 24 \times \textit{capacity factor} \times (1-A)}$$

A : Auxiliary power rate

4.2 O&M Cost

While the general method requires extensive calculations for O&M costs over plant's lifetime, KHNP's guideline simplifies it by using average annual O&M cost. O&M cost in LCOE is calculated using the below equation.

O&M cost in LCOE

$$= \frac{\textit{average annual O\&M cost}}{\textit{plant gross output}(kW) \times 365 \times 24 \times \textit{capacityfactor} \times (1-A)}$$

A : Auxiliary power rate

It should be noted that the average annual O&M cost should include all types of operation and maintenance costs regardless of their occurrence time. The annual O&M cost, therefore, should be calculated from averaging out annual O&M costs from a time period that is long enough to include plant equipment refurbishment.

4.3 Fuel Cycle Cost

KHNP's guideline for economic evaluation requires analyst to calculate the front-end fuel cost of nuclear power using the KHNP's fuel-cycle cost calculating code. The front-end fuel cycle cost consists of costs for uranium mining, milling, enrichment, and UO_2 fuel fabrication and interests for cost of each step are also included to capture the time value of money that arises from the time difference between fuel manufacturing process and its use in a reactor. Other fuel-related costs, such as fresh-fuel handling, in-site storage, and spent-fuel handling are to be included in O&M category.

The back-end fuel cost should be included in overall plant costs. In the KHNP's guideline, it can be included in the operation cost as a part of operation expenses. In this paper, however, it is included in the fuel cycle cost. The owner of a nuclear power plant should pay contributions for a fund of spent fuel management for all spent fuels generated from reactors. The contribution payment is to be used for interim storage and deep geological disposal. The spent fuel management cost was investigated by the Korean government calculation rule.

4.4 Decommissioning Cost

KHNP's guideline for economic evaluation requires analyst to reflect the cost of plant decommissioning considering the money amount that is needed to accumulate annually during the life of plant. The regulation of the Korean government (the Ministry of Trade, Industry and Energy) provides with the standard for decommissioning cost estimate (643.7 billion KRW for a unit of PWR) in their notification, Notification no. 2015-132(2015.06.30). KHNP's guideline requires analyst to apply the standard cost for economic evaluation and to calculate the annual accumulation for plant decommissioning.

Annual accumulation for a reserve fund of plant decommissioning
= 643.7 billion KRW × scale adjustment × escalation adjustment ÷ plant life (year)

The equation contains two adjustment factors. Scale adjustment reflects the difference between conventional PWR and a new plant (EU-APR in this report) considering technical aspects of plant size and quantity of radioactive wastes. Escalation adjustment is to reflect a price change from the base date of standard decommissioning cost (643.7 billion KRW), the end of 2014, to the base date of the economic evaluation. Decommissioning cost in LCOE is calculated with the annual accumulation as below.

Decommissioning cost in LCOE

$$= \frac{annual\ accumulation\ for\ a\ reserve\ fund}{plant\ gross\ output(kW) \times 365 \times 24 \times capacity factor \times (1-A)}$$

A : Auxiliary power rate

It is noted that the equation is not handling the decommissioning cost by discounting it to the base date of evaluation but treating it in constant value. Since the economic life of power plant is very long, decommissioning cost in LCOE usually diminishes into very small number when discounting is applied in the general method of LCOE calculation.

4.5 LCOE of EU-APR

The main result from the economic evaluation of EU-APR is summarized below.

Table 3. Comparison of EU-APR and APR1400 Cost Elements of LCOE

Category		Unit	EU-APR	APR-1400
LCOE	Capital cost	KRW/kWh	29.22	18.23
	O&M cost	KRW/kWh	11.94	11.94
	Fuel cycle cost	KRW/kWh	9.64	9.64
	Decommissioning cost	KRW/kWh	1.27	1.27
	Sum	KRW/kWh	52.07	41.08

※ Constant price(reference date 2016.01.01), Currency exchange rate: 1,100KRW/USD, Discount rate : 3.71%/y

4.6 Comparison to foreign reactors reported in 「OECD NEA/IEA 2015」

The following table shows the capital cost and LCOE of nuclear reactors of major countries that currently utilize nuclear energy as an energy source. They are referred from the report, 「Projected Costs of Generating Electricity, OECD NEA/IEA, 2015」, and the capital cost and LCOE of APR1400 and EU-APR were reevaluated using the economic parameters of the OECD NEA/IEA 2015 report.

Table 4. Comparison to foreign reactors reported in OECD NEA/IEA 2015

Country	France	Japan	USA	China	Korea	
Reactor	ALWR	ALWR	ALWR	ALWR	APR1400	EU-APR
Net Capacity (MWe)	1,630	1,152	1,400	1,250	1,395	1,395
LCOE (USD/MWh)	49.98	62.63	54.34	30.77	33.19	41.14
Comparison (□/EU-APR)	1.21	1.52	1.32	0.75	0.81	1.00

- Cost base date: 2013.06.30
- Discount rate: 3%, Capacity factor: 85%, Currency exchange rate: 1,095.37 KRW/USD

5. Conclusions

This economic evaluation, as an economic assessment report of EU-APR market diversification research project, has conducted a cost estimate of EU-APR and LCOE analysis with assumption that EU-APR is constructed and operated in Korea.

The design changes of EU-APR from APR1400 that improve the reactor to be complied with the up-to-date safety and performance requirements of nuclear regulators and utilities in Europe were considered to the cost estimate. The design changes include additional redundancy for the important safety functions, diverse measures for reactor shutdown and emergency power supply, secondary containment and the auxiliary building exterior wall and roof, SA mitigation systems, and 50 Hz frequency of AC electrical systems and their consequent changes in capital cost was analyzed.

As a result, the LCOE of EU-APR was calculated according to KHNP's economic evaluation guideline and it was estimated at 52.07 KRW/kWh which is 26.8% higher than APR1400.

After the Fukushima accident, a higher level of safety has being requested to nuclear power plants and it brings about cost increases. The reference plant of this evaluation, APR1400, is also expected to have raised capital cost due to reinforced safety concerns. It is expected that the global electricity market would continually require reactors with reinforced safety and economic competitiveness. Thus a development for reinforced safety should be continued and concerns for economic competitiveness, such as a further development of design optimization, passive safety and advanced construction method, also should be paid.

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