Preliminary economic analysis of Nuclear integrated Liquid Air Energy Storage System

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1. Introduction

For reducing Green House Gas (GHG) emission, many countries are replacing fossil fuel with Renewable Energy Sources (RESs), such as wind and solar Photo Voltaic (PV) [1]. However, the intermittency of RES causing issues regarding the stability of electric grid.

Nuclear Power Plant (NPP) can become sensitive to these RES induced fluctuations when RES penetration occurs in an accelerated manner. An NPP can control its power by inserting or ejecting control rod. However, frequent use of control rod may cause xenon oscillation and accelerate component degradation [2]. As a solution to this problem, nuclear integrated Liquid Air Energy Storage System (LAES) is proposed for increasing operational flexibility of NPP while keeping core power at constant.

LAES stores energy by liquefying air. When electricity is oversupplied, air is compressed and liquefied. When additional electricity is needed, air is evaporated and expanded to operate air turbine. Because air is stored as form of liquid, LAES has considerably high energy density leading less geographical constraint [3]. Park et al. proposed the mechanical integration between charging process of LAES and secondary side of NPP [4-5]. The integration is established by Steam Turbine-Driven-Compressor (STDC). The power of NPP is controlled by bypassing steam before Low Pressure Turbine (LPT) and the bypassed steam is used to operate STDC for transferring energy to LAES. The research team reported that mechanical integration can increase capacity factor of NPP while maintaining core power as constant. Reported round-trip efficiency of integrated LAES is 53% and energy density is 123.5kWh/m^3.

However, technical evaluations alone are not enough to further realize integration of LAES. In order to increase feasibility of integration, economic analysis is essential. Levelized Cost of Electricity (LCOE) is a typical economic value which measures the average net present cost of electricity generation for a power plant over its lifetime. By calculating LCOE, it can be evaluated that how economically LAES stores energy.

The purpose of this study is to calculate LCOE of nuclear integrated LAES. In this study, the LCOE calculation method of integrated system is proposed and the range of LCOE is presented with various economic parameters.

2. Methodology

2.1 Calculation method of LCOE

The typical LCOE is calculated as the ratio between all the discounted costs over the lifetime of a power plant divided by a discounted sum of the actual energy amounts delivered [6].

$$LCOE_{typ} = \frac{\sum_{t=1}^{n} I_t + M_t + F_t}{\sum_{t=1}^{n} E_t} \qquad \text{(Eq. 1)}$$

where I_t *is capital cost,* M_t *is operation and maintenance cost,* F_t *is electricity cost and* E_t *is generated energy.*

However, the LCOE of integrated LAES is different. There is no electricity consumption, because steam is the power source to operate air compressor rather than electricity. The definition of LCOE for integrated LAES is given as follow:

$$LCOE_{int} = \frac{\sum_{t=1}^{n} I_t + C_{STDC} + M_t + O_t}{\sum_{t=1}^{n} E_t} \qquad \text{(Eq. 2)}$$

where C_{STDC} *is cost of STDC and* O_t *is opportunity cost of NPP.*

The difference is that LCOE of integrated LAES contains cost of STDC and opportunity cost of NPP. Since additional steam turbine is needed for mechanical integration, the cost of STDC should be included. The electricity cost should be replaced with the opportunity cost of NPP, since the net power of NPP is decreased during charging process. The full definition of LCOE is given as follow:

$$LCOE_{int} = \frac{\sum_{t=1}^{n} \frac{I_t + C_{STDC} + M_t + O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{(Eq. 3)}$$

where r is discount rate and n is operation year of plant.

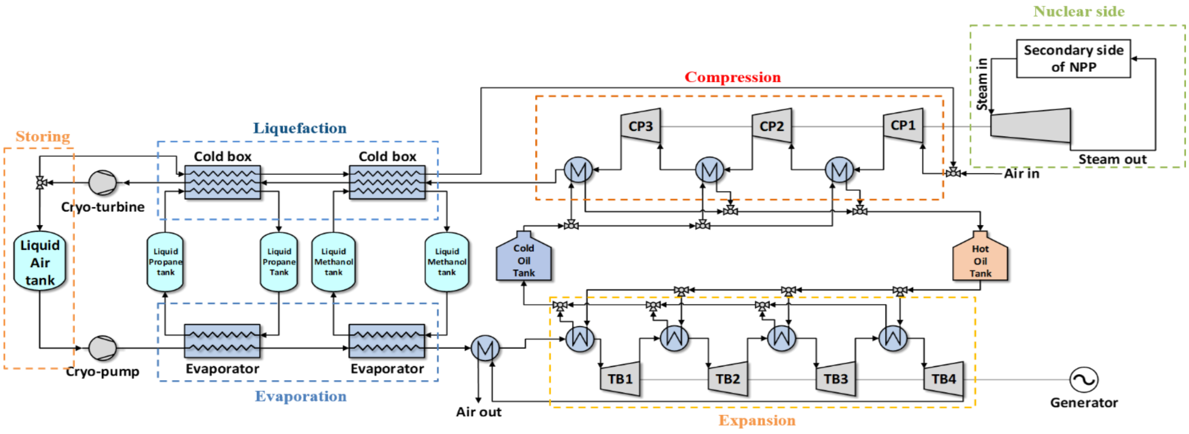

Fig. 1. Proposed layout of nuclear integrated LAES [4-5]

2.2 Cost categories of LCOE

LCOE is divided to various sub-items: Total Capital Investment (TCI), Operation and Maintenance Cost (O&M cost), electricity price, and yearly generated energy. First, in the light of TCI, TCI consists of two main accounts: Direct cost (DC) including Purchased Equipment Cost (PEC) and Indirect Cost (IC).

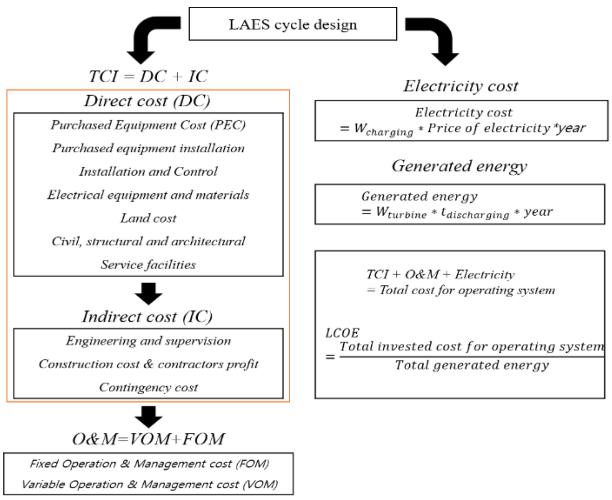

Fig. 2. Cost categories for the LCOE calculation

The main account in the DC is PEC. PEC includes all the component cost such as air compressor, heat exchanger, turbine, fluid, and tank cost. Therefore, PEC plays an important role in LCOE calculation. To calculate PEC, the previous research of economic analysis on the LAES is referred from Ref. [7] and the referred values are listed in Table 1. When calculating PEC, six-tenth law is applied. Six-tenth law describes a relationship between the increase in equipment cost and the increase in capacity. The equation is given as follow:

$$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^{0.6} \qquad \text{(Eq. 4)}$$

where C is equipment cost, V is equipment capacity, 1 is reference value, and 2 is input value.

Table 1. Referred PEC data [7]

Account	Reference cost	Reference capacity
Steam turbine	10M$	15MW
Motor	0.75M$	15MW
Air compressor	10.95M$	23MW
Air turbine	99.39M$	193MW
Thermal oil	$6.1/kg	N/A
Methanol	$400/ton	N/A
Propane	$0.23/kg	N/A
Cold box	3.79M$	$33MW_t$
Air-oil HX	0.44M$	$15.3MW_t$
Evaporator	1.60M$	$31.9MW_t$
Oil tank	$\$423/m^3$	$2185m^3$
Liquid air tank	$\$1548/m^3$	$3458m^3$
Propane tank	$\$1326/m^3$	$5643m^3$
Methanol tank	$\$572/m^3$	$1452m^3$
Cryo-pump	0.4	0.84MW
Cryo-turbine	0.4	0.84MW
Air-recuperator	0.44	$15.3MW_t$

By using the referred data and six-tenth law, approximate PEC is calculated. And the rest of cost including DC, IC, O&M cost is assumed, based on the equipment cost (i.e. PEC) [8]. The DC excluding PEC is the ratio to PEC and the IC is the ratio to total sum of DC. Also, O&M cost is the ratio to TCI. By considering this relationship between DC, IC, and O&M, the total invested cost is calculated (Table 2).

Table 2. Cost assumption of LCOE [8]

Account	Unit	Value	Base
Purchased equipment installation	%	20	PEC
Piping	%	10	PEC
Instrumentation & control	%	7	PEC
Electrical equipment and materials	%	10	PEC
Land cost	%	10	PEC

Civil, structural and architectural	%	30	PEC
Service facilities	%	30	PEC
Engineering and supervision	%	9.8	DC
Construction cost & contractors profit	%	1.19	DC
Contingency cost	%	15.0	DC
Fixed O&M	%	1.29	FCI
Variable O&M	%	9.0	FOM

2.3 Specification of nuclear integrated LAES

For calculating LCOE, the capacity of nuclear integrated LAES is referred from previous research [5]. For conducting sensitivity analysis of LCOE, the range of economic parameters are determined. Referred data and range of economic parameters are listed in Table 3.

Table 3. Specification of nuclear integrated LAES

Parameter	Value
Charging power	300MW
Charging time	8 hours
Discharging time	10 hours
Storage capacity	2.4GWh/day
Operating year	30 year
Discount rate	1~3%
Nuclear price	₩50~70/kWh
Number of cycles	100~365

3. Results and Discussion

3.1 Sensitivity analysis

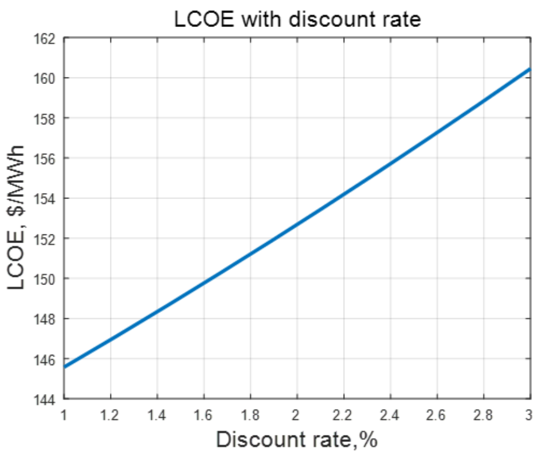

Fig. 3. LCOE with discount rate for one cycle per day and ₩60/kWh opportunity cost

Figure 3 shows the sensitivity of LCOE with discount rate. The discount rate converts the future value into Net Present Value (NPV). It means that high discount rate makes NPV low. Therefore, high discount rate causes high LCOE.

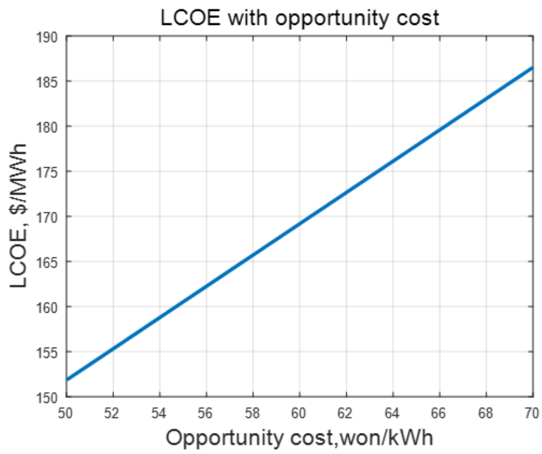

Fig. 4. LCOE with opportunity cost of NPP for one cycle per day and 1.5% discount rate

Figure 4 shows the sensitivity of LCOE with opportunity cost of NPP. As the opportunity cost increases, LCOE linearly increases. This is reasonable result because the LCOE includes opportunity cost rather than electricity price.

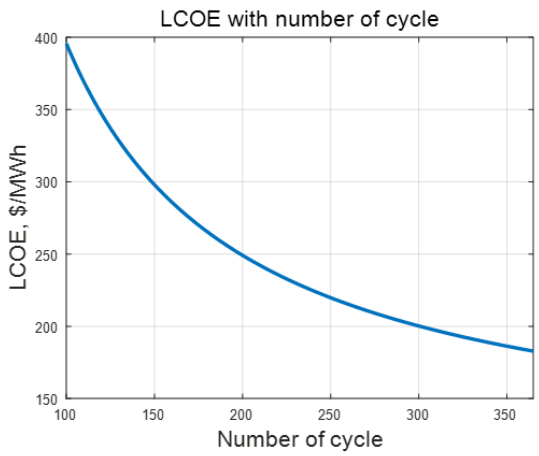

Fig. 5. LCOE with number of cycles at 1.5% discount rate and ₩60/kWh opportunity cost

Figure 5 shows the sensitivity of LCOE with number of cycles. As the number increases, LCOE decreases. This is because the generated electricity increases while the invested cost is the same.

From the sensitivity analysis, the range of LCOE is presented in Figure 6.

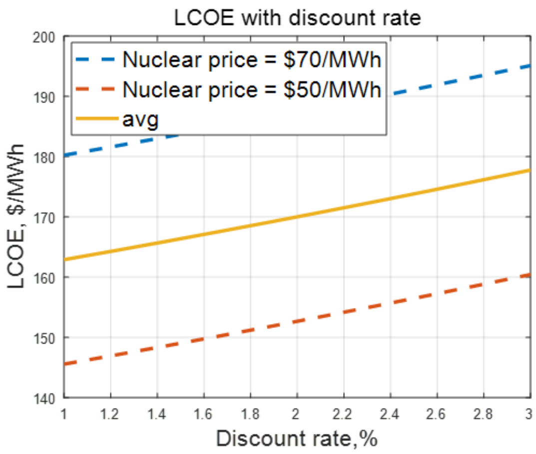

Fig. 6. The range of LCOE for one cycle per day operation

Figure 6 shows the range of LCOE with discount rate and nuclear price for a year while assuming charging and discharging processes occur daily. The range of LCOE is between $145/MWh and $190/MWh varying with discount rate and nuclear price.

4. Conclusions and further works

A preliminary economic analysis of nuclear integrated LAES is conducted in this study. To evaluate LCOE, the definition of LCOE for integrated system is newly proposed and various economic parameters are presented including TCI, DC, IC, and O&M. As a result of the sensitivity analysis, LCOE increases when discount rate increases which leads to reducing NPV and elevating opportunity cost. The range of LCOE with number of cycles per year is also presented. From the sensitivity analysis, the range of LCOE is located between $145/MWh and $195/MWh. The average value is around $170/MWh. However, this study contains many assumptions. Therefore, in the future, detailed economic indicators will be used to obtain LCOE with better accuracy. Furthermore, in order to demonstrate economic feasibility, a comparison with standalone LAES will be performed.

5. Acknowledgment

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REFERENCES

[1] New Energy Outlook in 2018, BNEF & IEA
[2] Technical and Economic Aspects of Load Following with Nuclear Power Plants, 2011
[3] Coleman, Justin, Shannon Bragg-Sitton, and Eric Dufek. An evaluation of energy storage options for nuclear power. No. INL/EXT-17-42420-Rev000. Idaho National Lab. (INL), Idaho Falls, ID (United States), 2017.
[4] Jung Hwan Park and Lee et al., “Preliminary thermodynamic analysis of LAES integrated nuclear power plant”, Transactions of the Korean nuclear society Spring Meeting, 2020.
[5] Jung Hwan Park and Lee et al., “Thermodynamic analysis of mechanically integrated liquid air energy storage sstem with nuclear power plant”, Transactions of the Korean nuclear society Autumn Meeting, 2020
[6] Lai, Chun Sing, and Malcolm D. McCulloch. "Levelized cost of electricity for solar photovoltaic and electrical energy storage." Applied energy 190 (2017): 191-203.
[7] Kim, J., Noh, Y., and Chang, D, 2018, “Storage system for distributed-energy generation using liquid air combined with liquefied natural gas”, Appl. Energy, 212, 1417-1432.
[8] 고아름, et al. "액화 공기 에너지 저장 기술 (LAES)의 경제성 분석." 신재생에너지 16.1 (2020): 1-14.