Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Economic Analysis of Liquid CO_2 Energy Storage System Integrated to a Conventional PWR

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1. Introduction

The energy production from variable renewable energy (VRE) sources is increasing globally and domestically. Globally, according to the United Nations World Climate Convention, the ratio of renewable energy (RE) is expected to increase to reduce greenhouse gas (GHG) emission. In Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE (including VRE) to 20% by 2030 [1]. However, as the proportion of VRE increases, major technical challenges also arise.

Solving the intermittency issue of VRE is one of the major challenges. Power generation from VRE is mostly affected by weather and climate conditions and therefore it cannot always generate power when the demand is high. This issue can be alleviated by load-following operation of a nuclear power plant (NPP). However, it is not economical to control power output of the reactor in an NPP. Energy Storage System (ESS) attached to the power cycle can solve this issue. Among various ESSs, compressed CO_2 energy storage (CCES) is promising ESS due to high round-trip efficiency (RTE) and simple layout.

CCES integrated to a conventional PWR was studied and analyzed thermodynamically in the previous study [2]. However, it had low energy density, 3.2kWh/m^3. For higher energy density, liquid CO_2 energy storage (LCES) with PWR was studied thermodynamically from liquefaction of CO_2 as shown in Figure 1 [3]. It has maximum RTE 51.8% and maximum energy density 12.8kWh/m^3. In order to evaluate the feasibility further, the economy of the proposed system should be evaluated and understand the associated cost.

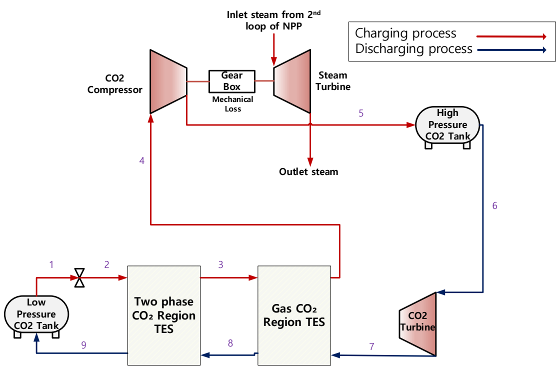

Figure 1. Layout of LCES integrated to PWR steam cycle [3]

Therefore, in this paper, economic analysis of a liquid CO_2 energy storage (LCES) integrated to a conventional PWR is presented. The economic performance of LCES in terms of the levelized cost of energy (LCOE) is presented in this paper.

2. Economic analysis

2.1 Levelized Cost of Energy

In this paper, levelized cost of energy (LCOE) is used among various indices of economic analysis. LCOE is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. It is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered as seen in the following equation.

$$\mathrm{LCOE}\left(\frac{\$}{\mathrm{MWh}}\right) = \frac{I_t + \sum_{t=1}^{n} \frac{M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : capital investment, M_t : operation and maintenance cost, F_t : electricity cost, r : discount rate, n : lifetime of power plant

I_t and M_t are can be calculated from the purchased equipment cost (PEC) and the Table 1 [4]. In this system, the compressor is driven by only steam turbine. In other words, it doesn't need the electricity to drive the compressor. However, PWR power production will be decreased during the charging process of LCES. Thus, F_t is the opportunity cost of unproduced electricity during the charging process. E_t is used from the previous thermodynamic study of LCES [3]. Thus, LCOE is evaluated from purchased cost of the components. The component cost is calculated from the power law form used for developing new cost model [5]. This cost model is used with scaling parameters (SP) of different components. Since the maximum temperature of LCES is below 550℃, the temperature correction factor is 1.

Table1. Ratio of LCOE details [4]

Account	Value
Total Cost Investment (TCI) = Direct cost + Indirect cost	
Direct cost (DC)	
Purchased Equipment Cost (PEC)	Sum of all components cost
Purchased equipment installation	20% of PEC
Piping	10% of PEC
Instrumentation & control	7% of PEC
Electrical equipment and materials	10% of PEC
Land cost	10% of PEC
Civil, structural and architectural	30% of PEC

Service facilities	30% of PEC
Indirect Cost (IC)	
Engineering and supervision	9.8% of DC
Construction cost & contractors profit	11.9% of DC
Contingency cost	15.0% of DC
Operation & Management Cost (O&M) = Fixed + Variable O&M	
Fixed O&M (FOM)	1.29% of TCI
Variable O&M (VOM)	9.0% of FOM

2.2 Heat exchanger

The scaling parameter of heat exchanger is overall conductance as shown in the following equation. The cost model is applied to two heat exchangers of two phase region TES and two heat exchangers of gas region TES.

$$C_{HX} = 49.45UA^{0.7544}$$

2.3 Compressor & Turbine

The scaling parameter of compressor and turbine is power consumed and produced as shown in the following equations, respectively. It is used for CO_2 compressor and turbine.

$$C_{Comp} = 1{,}230{,}000W_{Comp}^{0.3992}$$

$$C_{Turb} = 182{,}600W_{Turb}^{0.5561}$$

2.4 Tank

The scaling parameter of tank is the volume of tank as shown in the following equation. It is used for CO_2 low-pressure and high-pressure tanks and four tanks in TES.

$$C_{Tank} = 40420V_{Tank}^{0.506}$$

2.4 Others

Since steam turbine and motor for this specific configuration do not have cost model, the six-tenth law is applied to the general data of steam turbine and motor. Six-tenth law show a relationship between the cost and the capacity of component as shown in the below equation.

$$\frac{C_1}{C_2} = (\frac{V_1}{V_2})^{0.6}$$

Table2. Cost and capacity of reference equipment

Equipment	Reference cost	Capacity
Steam turbine	10M$	15MW
Motor	0.75M$	15MW

2.5 Modeling parameters

Table3. Design parameters of LCES

Parameters	Value	Unit
Charging time	8	hr
Discharging time	8	hr
Lifetime	30	yr
Discount rate	5	%
Nuclear price	62	$/MWh

Table4. Variables of LCES

Parameters	Range of Variation	Unit
Pressure of low-pressure reservoir	0.6-3.4	MPa
Pressure of high-pressure reservoir	20-30	MPa

The design parameters are shown in Table 3 and the variables and ranges of variation are shown in Table 4.

3. Results

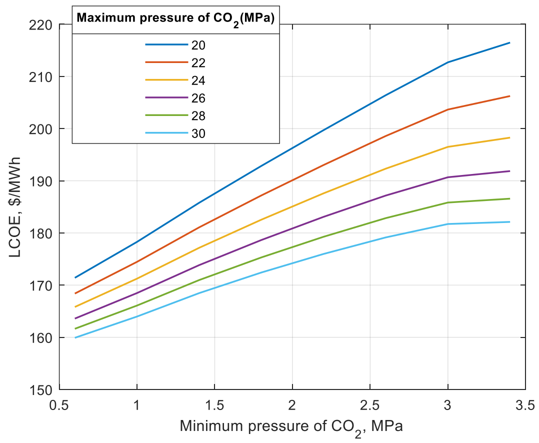

Figure 2. LCOE vs Minimum and maximum pressure of system

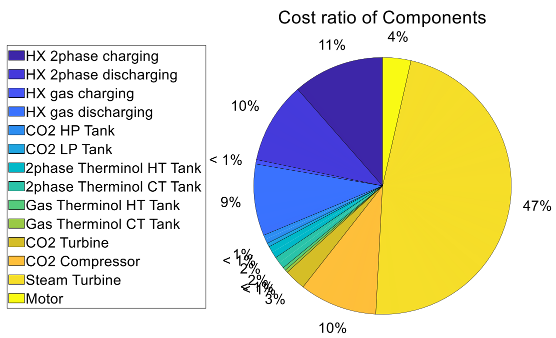

Figure 3. Cost ratio of components

In this paper, LCOE is evaluated from the aforementioned models and Tables. As shown in Figure 2, it has the LCOE reaches $160~220/MWh. As the maximum CO_2 pressure increases and the minimum CO_2 pressure decreases, LCOE decreases. When the minimum and the maximum pressure are 0.6MPa and 30MPa, respectively, it has the lowest LCOE of $160/MWh. From the previous thermodynamic study, it showed the best performance at the same optimized condition. In other words, large pressure ratio shows better economic and thermodynamic performances.

Figure 3 shows the cost ratio of LCES components. As shown in the figure, in this system, the turbomachinery is the most expensive component, followed by the heat exchangers.

4. Summary and Future works

From the result of the liquid CO_2 energy storage economic analysis, it is shown that as the maximum pressure increases and the minimum pressure decreases, LCOE decrease. The lowest LCOE is expected to be $160/MWh. The optimized operating conditions have the highest RTE and energy density, and the lowest LCOE.

LCES can have various layouts. Thus, in the future, economic analysis of various layouts will be explored to investigate possibility of further decreasing the LCOE of the proposed system.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (2019M2D2A1A02059823)

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