

Economic analysis of Liquid Air Energy Storage System with Small Modular Reactor

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1. Introduction

Small Modular Reactor (SMR) is an attractive option for energy supply where a huge power plant cannot be installed [1]. Small power output for SMR will be appropriate for a small grid. Moreover, regional constraint such as river or oceans to supply huge amount of coolant to build a nuclear power plant is removed in SMR. These features of SMR attract countries with small grids.

Due to increasing interest on SMR, the research on innovative SMR itself is underway but also, the research on an integrated system with SMR to increase its efficiency of maximize benefit is actively progressing. SMRs coupled with wind energy, energy storage, and hydrogen production via high-temperature steam electrolysis [2] are good examples.

In this paper, an economic analysis on the Liquid Air Energy System (LAES) combined with SMR is presented to show the feasibility of the mechanically integrated ESS with SMRs. As an example, a standalone LAES and SMR integrated LAES are compared in terms of LCOE. The size of the integrated SMR is 486MWth and the steam after high pressure turbine will be split to steam turbine driven compressor in the LAES (fig.1).

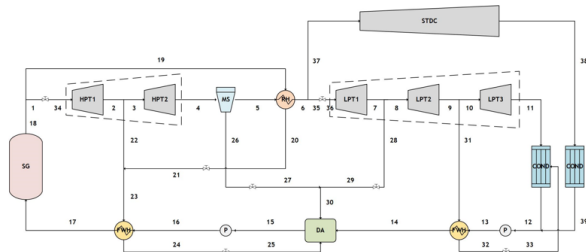


Figure 1. Layout of Secondary Cycle for Small Modular Reactor

Before the economic analysis, the inlet temperature of the steam generator was checked to ensure that there was no problem with the secondary side of the SMR when the steam inside the SMR was branched. The Levelized Cost of Electricity (LCOE) is calculated up to 50% steam split for an SMR. The LCOE for SMR follows work of Boarin et al [3]. The SMR cycle and integrated system are calculated by an in-house code built in MATLAB (KAIST-CCD).

2. Methodology

The LCOE is essentially the total lifecycle cost for a system divided by the lifetime energy production [4].

$$LCOE = \frac{\text{Lifecycle Cost}(\$)}{\text{Lifetime energy productuin}(kWh)} \quad (eq. 1)$$

This can be expressed as in eq.2:

$$LCOE = \frac{\Sigma(I_t + M_t + F_t)}{\Sigma E_t} \quad (eq. 2)$$

I_t : capital investment

M_t : operation and maintenance cost

F_t : electricity cost

E_t : generated energy

For the integrated system, LCOE will follow eq.3 which an added cost for steam driven compressor and opportunity cost of SMR should be reflected:

$$LCOE = \frac{\Sigma(I_t + M_t + F_t + C_{STDC} + O_t)}{\Sigma E_t} \quad (eq. 3)$$

C_{STDC} : cost for steam turbine driven compressor

O_t : opportunity cost of SMR

The opportunity cost of SMR follows the case summarized in the table below.

Table 1. LCOE for Large Reactor and SMR (re designed from [3])

| | Supported Case | | Merchant Case | |
|--------------|----------------|------|---------------|------|
| Reactor Type | Large Reactor | SMR | Large Reactor | SMR |
| LCOE(\$/MWh) | 55.0 | 59.1 | 96.1 | 96.3 |

The final LCOEs of standalone case and nuclear integrated case considering discount rate and operating year will be eq.4 and eq.5, respectively

$$LCOE_{standalone} = \frac{\Sigma_{t=1}^n \frac{(I_t + M_t + F_t)}{(1+r)^t}}{\Sigma_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (eq. 4)$$

$$LCOE_{integrated} = \frac{\Sigma_{t=1}^n \frac{(I_t + M_t + F_t + C_{STDC} + O_t)}{(1+r)^t}}{\Sigma_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (eq. 5)$$

The parameters for LCOE calculation are shown in the table below, and the specific cost of equipment follows Kim et al. study [5].

Table 2. Economic Parameter

| Parameter | Value |
|--------------------------|-----------|
| Operating year | 60 year |
| Discount rate | 1.2% |
| Construction year | 2 year |
| Electricity price | 120\$/MWh |
| Charging time of LAES | 10 hours |
| Discharging time of LAES | 10 hours |
| Number of cycles in year | 365 |

3. Results & Discussions

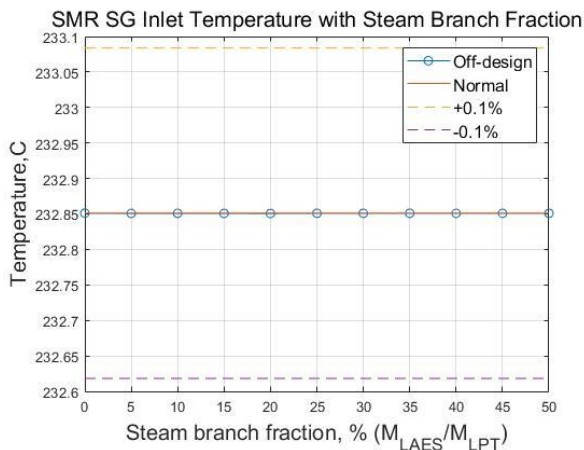


Figure 2. Steam Generator Inlet Temperature

As shown in fig.2, there is no substantial temperature change in the SMR steam generator inlet temperature due to steam bypassing to LAES. Up to 50% steam branch after high pressure turbine is possible, and there is no significant temperature change in the SG inlet temperature.

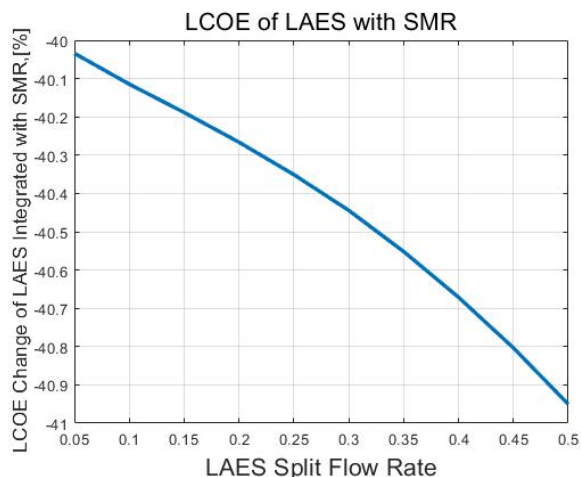


Figure 3. LCOE of Standalone and Integrated LAES System

Following the conditions shown in table 2, the mechanical integration of LAES and SMR shows nearly 40% of decrease in LCOE compared to standalone LAES system. As shown in fig. 3 there is no significant LCOE difference with respect to the split flow rate of SMR to LAES system. Although there is nearly 1% of difference

in LCOE for the minimum split rate (0.05) and the maximum split rate (0.50), this is not substantial change on the system. Therefore, SMR integrated LAES system could be operated in various situations. This will make SMR more flexible and economical while preserving economic performance.

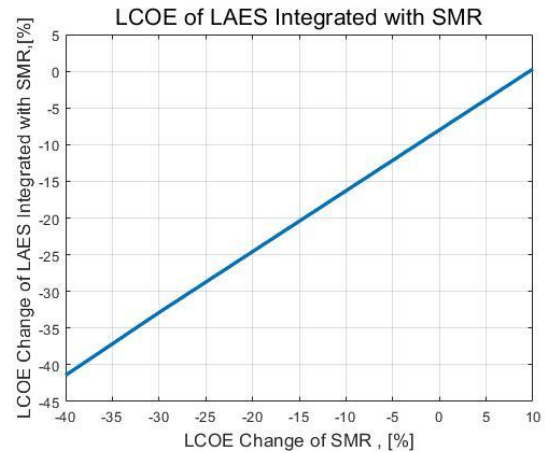


Figure 4. Integrated System LCOE trend following change of SMR LCOE

The LCOE of the SMR integrated LAES system decreases with the decrease of SMR LCOE. As shown in Figure. 4, for 40% decreased SMR LCOE case can reduce LAES LCOE by 60% compared to the standalone LAES system. In the case of upper bound 10% increase of SMR LCOE from the reference value still shows 35% LCOE decrease for the SMR integrated LAES system. This trend shows that further technical advancement and economic improvement in SMR can make LAES system more favorable.

4. Conclusions and Future Works

When SMR and LAES systems were linked, it was confirmed that there was no considerable change in SMR's steam generator inlet temperature. Although it is concluded that the LAES system linkage does not cause any issues in terms of affecting the steam power cycle conditions, there is still a lack of research under transient conditions of SMR. Therefore, further studies will be conducted if SMR's steam branch can cause any issues under transient conditions.

Furthermore, there was no significant change in the LCOE of NPP-LAES-linked systems according to the steam split fraction. NPP-LAES-integrated systems could operate flexibly under various situations. Further research is needed on how these changes affect the operation of SMRs when dynamically controlling the steam fraction. Finally, this paper analyzed the sensitivity of LCOE of the integrated system to the SMR's LCOE. It is shown that the integrated system's LCOE decreases with the LCOE of SMR decrease. However, extensive comparative analyses with hydrogen systems or other types of ESS systems with SMR are necessary to demonstrate that the strength of LAES integrated SMR.

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