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Comparison Analysis of Thermal and Mechanical Integrated Liquid Air Energy Storage Systems with Pressurized Water Reactor

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1. Introduction

The worldwide environmental and climate concerns led to increase in renewable energy. However, renewable energy such as wind and solar power expected to hold large portion in renewable energy substantially depend on the environmental condition and time. To reduce this uncertainty in energy supply, an Energy Storage System (ESS) is necessary [1].

In Korea, nuclear power has a high proportion of base load. Although the PWRs were originally designed to be able to do load-following operation, further development can improve its maneuverability while maintaining the safety margin and reducing the effluent release. [2] The integration of Nuclear Power Plant (NPP) and ESS can be one of the candidate technologies.

In this paper, the comparative analysis of two Liquid Air Energy Storage (LAES)-NPP integrated systems is presented. The LAES systems were integrated with NPP in two ways in this paper. The first method is to integrate the NPP steam in the discharging cycle of LAES. This method is thermal integration of LAES with NPP. The second method is to operate the compressor in the LAES charging cycle with steam turbine which is operated by steam from NPP. This method is mechanical integration.

The comparison of two methods will give insight to design that combines LAES and NPP. As two systems have different sensitivity to certain thermal parameters, it will help to choose and design a system that is more appropriate for a given constraint. Cycle performances are calculated by in-house code built in *MATLAB* (KAIST-CCD).

2. Methods

2.1 NPP Side Calculation

As two types of integrated system receive steam from NPP, the steam properties will be obtained from the on-design and off-design steam cycle models [3]. In this process the split steam flow from NPP changes the total power generation from NPP and power reduction is considered as the opportunity cost in the Round Trip Efficiency (RTE) of the integrated system. The detail of RTE calculation will be explained for each system in the next section.

2.2 Thermal integration

For the thermal integration, the LAES layout shown in Fig. 1 is used. This cycle was suggested from the previous work [4]. In this paper, the loss from NPP side is calculated for off-design conditions [3] to improve accuracy of NPP power loss. Moreover, the isothermal compressors are replaced with adiabatic compressor for realistic system modeling. As show in figure 1, in the thermal integration system, the steam flow from NPP heats air before air enters air turbine in the LAES discharging cycle.

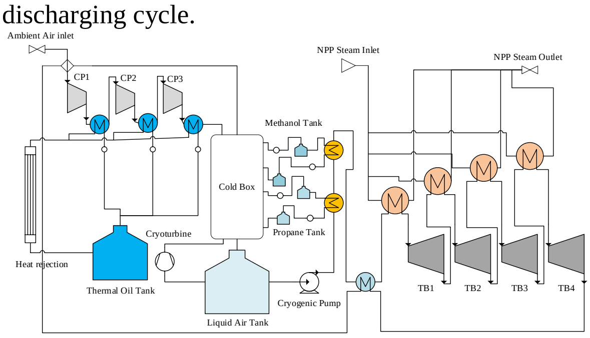

Figure 1 Thermal integration LAES system

The RTE is calculated by ratio of total generated energy to total consumed energy. In the thermal integrated system, the total generated energy is a sum of generated electricity from air turbine, energy loss from NPP due to split flow of steam, and power loss from pumps in the discharging cycle. The total energy consumption is a sum of pump and compressor in the charging cycle. [Eq.1]

$$\mathrm{RTE} = \frac{\left(P_{LAES,disc} - P_{loss,NPP}\right) \cdot \left(T_{disc}\right)}{\left(P_{LAES,char}\right) \cdot \left(T_{char}\right)} \qquad [\mathrm{Eq.\,1}]$$

$$\mathbf{P_{LAES,char} = P_{CP,char} + P_{pump,char} - P_{cryoTB,char}} \quad [\mathbf{Eq.2}]$$

Equation 2 is the total power consumption to operate LAES charging cycle for unit time. It is a sum of consumed compressor work and pump work with produced cryogenic turbine work in unit time.

$$\mathbf{P_{LAES,disc} = P_{TB,disc} - P_{pump,disc}} \quad [\mathbf{Eq.\,3}]$$

Equation 3 is the total power generation from LAES in unit time. It is a sum of total power generation from air turbine in discharging cycle and power consumption from pump in discharging cycle. To operate thermal integrated LAES system, the loss from NPP is generated in discharging time. Therefore, the total power generation from discharging cycle is the difference between power from LAES and power loss from NPP. Finally, the RTE is a multiply of ratio of power generation and power consumption, and the time ratio between discharging cycle operation and charging operation.

2.3 Mechanical integration

In the mechanical integration system, the steam flow from NPP runs turbine which operates turbine driven compressor in the charging cycle [Fig. 2]. As the mechanical integration cannot deliver turbine work to compressor work, the mechanical loss factor is considered.

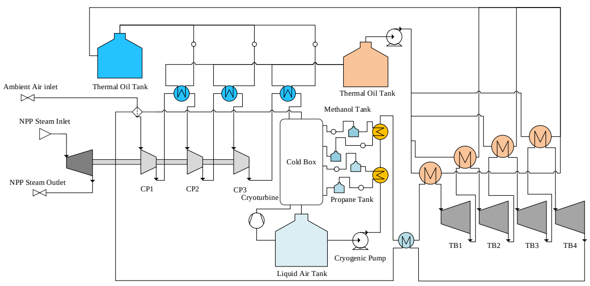

Figure 2 Mechanical Integration LAES system

In the mechanical integration system, the RTE is different from Eq. 1. As the integration between LAES and NPP is on the charging cycle, the power loss from NPP term is in the power consumption of total system [Eq. 4].

$$\mathrm{RTE} = \frac{(\mathrm{P}_{\mathrm{LAES,disc}})\cdot(\mathrm{T}_{\mathrm{disc}})}{(\mathrm{P}^{*}_{\mathrm{LAES,char}})\cdot(\mathrm{T}_{\mathrm{char}})} \qquad \text{[Eq. 4]}$$

In the changed LAES charging power, the power loss from NPP is replaced with the power consumption of compressor in charging cycle [Eq. 5].

$$\mathrm{P}^{*}_{\mathrm{LAES,char}} = \mathrm{P}_{\mathrm{loss,NPP}} + \mathrm{P}_{\mathrm{pump,char}} - \mathrm{P}_{\mathrm{cryoTB,char}} \qquad \text{[Eq. 5]}$$

The total power generation is difference between air turbine power generation and power consumption form pump [Eq.3]. As same in equation 1, the time ratio of discharging and charging cycle is multiplied to final RTE.

2.3 Constraints for comparison

In this paper, the RTEs of two systems under the same constraint are compared [Table. 1].
Charging time is 5 hours and discharging time is 1 hour. This is the condition in which the ratio of charging to discharging can be the greatest under the given constraint.

Table 1 Condition of NPP

NPP parameter	value
steam inlet temperature	540(K)
steam inlet pressure	1443(kPa)
steam mass flowrate	298(kg/s)
Power loss from NPP	261(MW)

3. Results

3.1 Thermal integration

Table 2 Energy Generation and Consumption of Thermal Integration

Energy consumption/generation	Value (MWh)
Charging	
Compressor	1167
Turbine	40
Pump	5
Total	1132
Discharging	
Turbine	633
Pump	18
NPP	261
Total	354
Round-trip efficiency	31 (%)

As shown in table 2, the thermal integration system has 31 percent of RTE. The energy needed for 5hours of charging cycle is 1167 MWh and the total energy produced in discharging cycle is 633 MWh. It may seem that RTE is near 50%, but as defined in equation 1, heat exchanger between air turbine use steam to reheat air flow after expansion. Therefore, the energy loss from NPP (opportunity cost) decreases the total energy output of the discharging cycle.

3.2 Mechanical integration

The mechanical integration system uses turbine driven compressor which uses steam to drive compressor. Thus, the compressor energy consumption is replaced by energy loss from NPP [Table. 3]. The NPP energy loss from mechanical integration system is higher than the compressor energy consumption from thermal integration system. It is due to the mechanical loss from turbine to compressor.

Table 3 Energy Generation and Consumption of Mechanical Integration

Energy consumption/generation	Value (MWh)
charging	
NPP	1305
Turbine	40
Pump	5
Total	1270
discharging	
Turbine	676
Pump	18
Total	658
Round-trip efficiency	52 (%)

In addition, as NPP is integrated with charging cycle, the total energy loss from NPP is 5 times higher than the thermal integration system. The total energy to run charging cycle is higher than the thermal integration system.

The discharging cycle has higher turbine energy generation. This is due to mechanical integration layout having higher inlet temperature when entering turbine. It has average 510K of temperature after heat exchange with thermal oil, however, thermal integrated system has average 477K of temperature after heat exchange with steam from NPP. This difference between two temperatures end up with about 43MWh of energy production more.

4. Conclusions and Future Works

The two system were compared under the same NPP condition. The thermal integration system from the previous work is used. The calculation of NPP side is improved and the isothermal compressors are replaced by normal compressor for better representation of the system.

The thermal integration system has lower RTE than the mechanical integration system. Its RTE is 31%, which is 21% lower than the mechanical integration. The main reason of RTE difference is due to the combination method of NPP and LAES system. Additionally, the thermal energy gap between steam and thermal oil affected the total turbine energy in the discharging cycle.

Although mechanical integration could achieve higher RTE than the thermal integration, this result is limited to the given NPP constraint. The NPP condition could be optimized for each method, and it will need to consider whether these conditions are satisfactory within the limitations imposed on realistic system deployments or not. Finally, the economic analysis should be accompanied for load-following operation of NPP.

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