Thermodynamic assessment of APR1400 integrating the liquid air energy storage

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1. Introduction

The recent global trends to reduce greenhouse emissions are trendin towards developing and installing clean energy. It has become more urgent to employ direct action to target the 2 Degree scenario set by the UNFCCC. Among the technology candidates for this ambitious goal, solar, wind, biomass, and nuclear energy are all mentioned as vital role-players in the climate change crisis [1].

To integrate a significant portion of renewable energy into the existing electricity grid, the problem of intermittency in most renewable sources must be addressed. The IRENA report suggested the renewable energy portion to increase up to two-thirds of the total world energy share by 2050 [2]. The issue requires either a substantial backup power led by conventional natural gas plants fit for agile generation or large capacity of energy storage systems. Both pose issues regarding economics as well as environmental feasibility. The natural gas plants still emit CO_2 unless captured by costly carbon capture and storage, while the commercial large-size batteries still face the materials and cost issue for scaling up to grid level.

On the other hand, nuclear power has been around for several decades to provide clean, cheap, and steady electricity. The issue, however, lies in the political resistance as well as economic difficulties for new builds. New designs, though promising, still need to wait more years to commercialize and to contribute to the CO_2 reduction in time.

Due to the increasing demand to resolve the intermittency issue in renewable energy, the flexibility in nuclear plants has also been explored. One of the options to adapt to the new grid condition is load-following. According to the European Utility Requirements for LWR Nuclear Power (EUR), the European nuclear power plants are required to operate between 50% and 100% of the rated power [3]. However, the nuclear power plant is limited by the ramp rate allowed by the design, and the load following mode is known to increase the operation costs.

Another option of integrating the energy storage system (ESS) has been investigated recently worldwide. The objective of such efforts is to retrofit the existing nuclear plant to reduce the impact of the conventional operation yet allow flexible power generation. One of the ways to synergize in the ESS integration is to make use of the constantly available heat source from the steam generation.

Recently, integrating the liquid air energy storage (LAES) with the conventional PWR plants has been investigated [3]. The liquid air energy storage utilizes energy stored in liquid air by using excess electricity and runs a fast responding power system to generate power at high demand.

This research addresses the issue of whether the LAES can be integrated to the existing APR1400 model. The paper covers the thermodynamic assessment of how to retrofit the existing model to operate within the given design conditions.

2. Design methodology

The ARP1400 model has been designed to generate roughly 1400 MWe, under the given design conditions in Table 1. To retrofit the plant so that the primary side would not be affected, only the secondary side should bypass enough steam flow to maintain equal inlet and outlet temperatures of the steam generator. The schematic of the integrated system has been modified from Li et al. [4].

In this calculation, the main focus is the energy discharge cycle, assuming that the liquid air has been produced through the energy storage cycle by operating an air liquefaction plant. It is assumed to be connected thermally to the hot side of the air evaporator, and its cold byproduct is stored to enhance the cold performance.

The thermodynamic calculation is performed by the in-house KAIST-CCD code that utilizes the thermophysical properties of NIST REFPROP. The calculation runs until the mass flow rate of the liquid air converges to a reasonable error bound, as it is adjusted to

Table 1. Design parameters of the APR1400 integrating the LAES

Design parameters	Values
Reactor thermal output	3983 MWth
Plant efficiency	35.1%
Steam temperature	285°C
Feedwater flow rate	2261 kg/s
Feedwater temperature	232°C
Steam pressure	6.9 MPa
Ambient temperature	25°C
Percentage of steam bypass flow	10%
Isentropic efficiency of air turbines	90%
Isentropic efficiency of cryogenic pump	70%
HX pinch temperature	5 K
LAES storage mode work consumption	76.7 MW
LAES storage mode production rate	150 kg/s

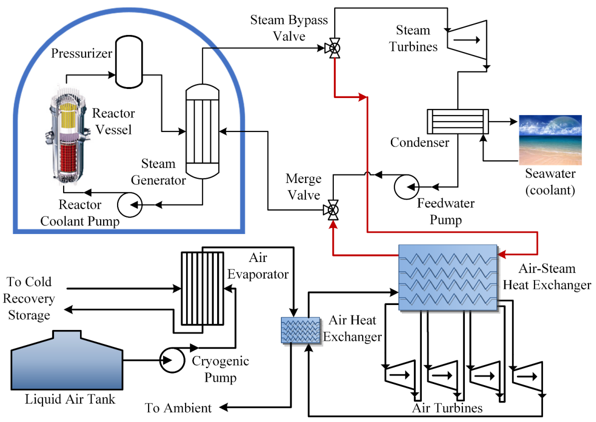

Fig 1. Schematic of APR1400 integrating the LAES

satisfy the energy balance in the air-steam heat exchanger. Pressure drops of the heat exchangers are neglected in the calculation.

The equation to calculate the round trip efficiency of this integrated system is the following:

$$\eta_{round-trip} = \frac{W_{discharge} - r \cdot Q_{NPP} \cdot \eta_{NPP}}{W_{storage}} \cdot \left(\frac{\dot{m}_{LAES,prod}}{\dot{m}_{LAES,discharge}}\right) \quad (1)$$

($W_{discharge}$: work produced during discharge cycle, r: percentage of steam bypass, Q_{NPP}: reactor heat, η_{NPP}: efficiency of NPP, $W_{storage}$: consumed work during storage mode, $\dot{m}_{LAES,prod}$: production rate of LAES during storage mode, $\dot{m}_{LAES,discharge}$: discharge rate of LAES)

3. Design analysis and results

Before setting the optimal point for design, parametric study has been performed to evaluate the effect of changing the key design parameters, number of air turbines installed and the maximum pressure raised in the system.

When observing the trend of increasing the number of turbines, it can be seen that the round trip efficiency rises with lowered mass flow rate of liquid air. In other words, having more turbines will reduce the required mass flow rate to run the system and therefore, increase the overall round trip efficiency. Having more number of turbines can reduce the power generated and instead increase the discharge time of the system.

Furthermore, increasing the maximum pressure raised by the cryogenic pump leads to higher round trip efficiency, as shown in Fig 3. This constraint is mostly bounded by the design limitation of the cryogenic pump and the costs involved in retaining a high pressure boundary. The design result under selected conditions is listed in Table 2.

4. Conclusion and further works

Integrating the APR1400 with the LAES under the objective of minimizing primary side temperature changes is studied thermodynamically.

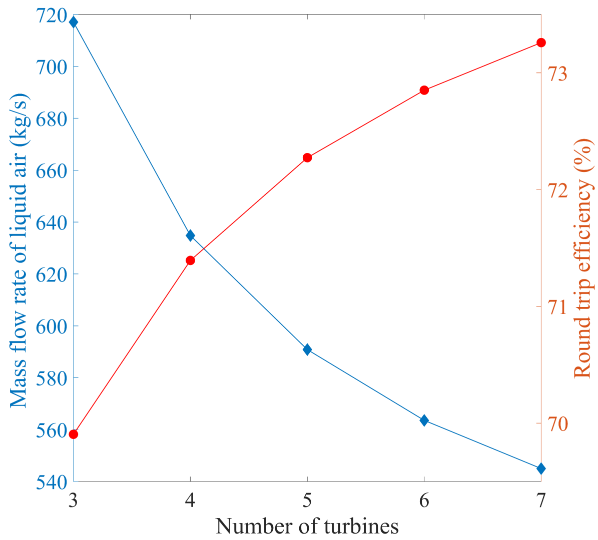

Fig 2. Number of turbines vs. mass flow rate and round trip efficiency

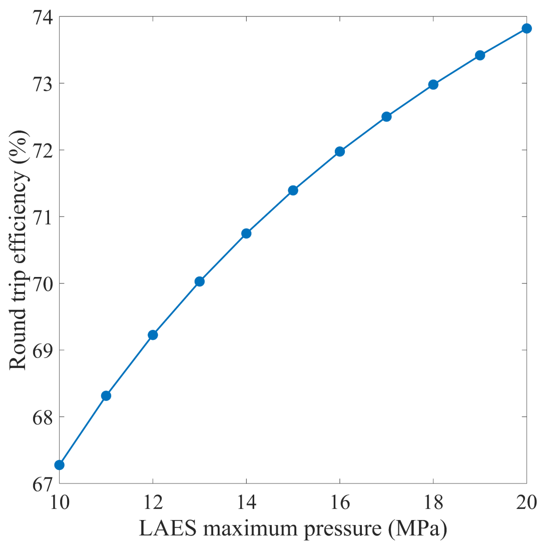

Fig 3. LAES maximum pressure vs. round trip efficiency

Table 2. Design results of the APR1400 integrating the LAES

Design results	Values
LAES maximum pressure	15 MPa
Number of turbines	4
Turbine work	387 MW
Pump work	15 MW
Round trip efficiency	71.4%
Air mass flow rate	635 kg/s

Bypassing 10% of the steam flow before entering the steam turbines can ramp up the power generation by nearly 2.7 times. Also, the maximum pressure can be increased to enhance the round trip efficiency, as long as the design limitations allow.

REFERENCES

[1] Vine, Doug, and Timothy Juliant. "Climate solutions: the role of nuclear power." Center for Climate and Energy Solutions (2014).
[2] IRENA (2018), Global Energy Transformation: A roadmap to 2050, International Renewable Energy Agency, Abu Dhabi.
[3] Lokhov, Alexey. "Technical and economic aspects of load following with nuclear power plants." NEA, OECD, Paris, France (2011).
[4] Li, Yongliang, et al. "Load shifting of nuclear power plants using cryogenic energy storage technology." Applied energy 113 (2014): 1710-1716.