Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Potential of applying liquid air energy storage to large-scale nuclear power plants for the APR1400 application

Jin Young Heo [a*], Jeong Ik Lee [a]
[a]*Department of Nuclear and Quantum Engineering, KAIST, Daejeon, South Korea*
Email: jyh9090@gmail.com, jeongiklee@kaist.ac.kr

1. Introduction

The global effort to reduce carbon emissions has led to the stark increase in the deployment of clean energy technologies. Because most of them extract energy from natural sources including solar and wind, they inevitably suffer from intermittency, a drawback of having a grid with high renewable penetration. Thus, the grid dynamics will naturally involve more fluctuation and consequently require increased energy storage systems (ESS).

On the other hand, conventional large-scale nuclear power plants (NPPs) have played the role of baseload power providing stable electricity to the grid. Providing electricity capacity in the GW-level, these offer stable electricity at low operating costs yet with high initial investment. However, as renewable penetration increases, the need for base-load power lessens, and instead, the excess generation may impose downregulation of the NPPs which leads to the increased cost of production due to changes in the load [1]. The cost of load-following is that it will bring problems in the equipment integrity as well as issues in economic and safety aspects [2].

In order to solve the issue of intermittency using the conventional large scale nuclear power systems, research efforts shown in previous references have attempted to enable efficient load-following of NPPs [3,4]. Various hybrid solutions using energy storage systems have been suggested, but in this research, the potential of adopting a novel concept of liquid air energy storage (LAES) is examined in this paper.

A concept firstly introduced by Smith (1977), liquid air energy storage, or also called cryogenic energy storage (CES), is a technology that utilizes cryogen in the form of liquid air or nitrogen as a storage medium [5]. Liquid air is generated using an air liquefaction cycle during off-peak hours when electricity is cheap. It is stored until electricity is required, and liquid air is pumped to increase pressure and heated to ambient or heat source temperature for turbine expansion. A schematic of LAES using cold thermal and heat storage modifications to the layout is shown in Fig. 1 [6].

The advantages of using LAES over other large scale energy storage systems are desirable in many aspects. Two main technologies considered for large-scale energy storage at the present are pumped hydropower and compressed air energy storage (CAES). However, they both suffer from geological restrictions, high capital costs, and negative environmental impact [7]. LAES presents the advantages of having larger volumetric energy density as well as having no geological constraints [8]. Hence, this concept can be integrated effectively with the large scale conventional NPPs in order to meet the demands of the transforming grid.

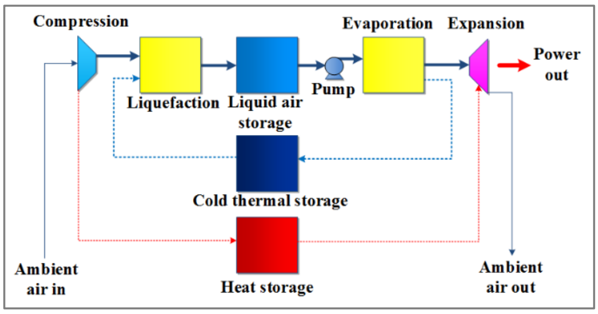

Fig. 1. Schematic of LAES with storage options [6]

2. Case study: potential of integrating LAES to the existing APR1400 in the Middle East

Because the countries in the Middle East have recently grown interests towards carbon-free energy such as nuclear power and solar, the energy grid dynamics is expected to change due to the intermittency from solar. Fig. 1 displays a forecast of the demand and production in Abu Dhabi, UAE in the winter of 2025. It can be seen that mainly the combination of baseload nuclear power, conventional fossil power plants, and solar power satisfies the total demand together.

However, it can be seen that even new solar is added dominantly for the Middle East region, further solar penetration would bring an imbalance in the overall grid. Thus, large size (grid level) energy storage systems are essential in order to bring about further deployment of carbon-free energy. In this context, the previously mentioned concept integrating large-scale nuclear power and LAES appears desirable because by time-shifting the significant baseload provided by the NPPs, the grid can withhold more capacity of solar.

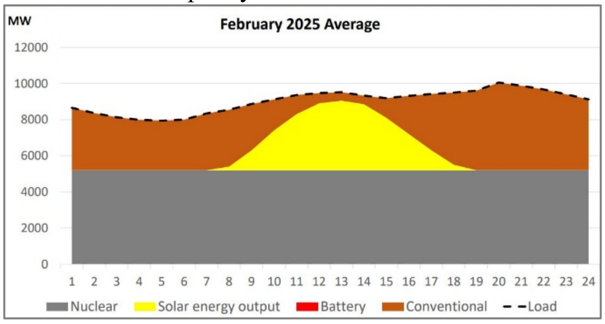

Fig. 2. Winter 2025 Daily Demand/Production Profile with 5000MW of uncurtailed solar PV installed for Abu Dhabi, UAE (Courtesy of ADWEC, [9])

Furthermore, integrating closely the existing large-scale nuclear power can bring improvements to the performance. Several integration concepts using LAES have been devised in previous efforts [1], and it is known that synergies with other processes such as cooling and recovering thermal sources can increase the overall efficiency of LAES system [8]. For the specific case of APR1400 design in the Middle Eastern context, several conceptual options can be assessed to understand the potential of applying LAES to the existing system.

The theoretical performance of the LAES can be expressed as:

$$\chi = y\frac{(W_t - W_p)}{W_c} \quad (1)$$

where y is the yield (mass of liquid/total mass) during the expansion process, W_t is the turbine work, W_p is the pump work, and W_c is the compressor work.

In order to maximize the work availability of both systems, the thermal coupling of the LAES and the nuclear power plant needs to be considered. One possible option would be to split the exiting flow from the steam generator and to connect it through the heat storage or heat exchanger prior to the turbine expansion stage, as demonstrated in Li et al. [1]. This way, the turbine inlet temperature can be risen up to 285°C, which increases the overall W_t . This option, however, involves a significant change in the current design of the APR1400, and would involve a careful control of the secondary side steam flow which is not desirable in the safety perspective.

Another option is to make better use of the waste heat from the discharge coolant exiting the condenser. Considering the Arabian gulf seawater temperature stays near 35°C, the coolant outlet temperature becomes nearly 43°C [10]. This low-grade waste heat is more readily available for usage in the LAES system to raise the turbine inlet temperature without involving substantial design changes in the overall nuclear secondary system. Considering the design constraints of the APR1400, the second option may become a more realistic alternative to integrating LAES into the nuclear plant.

3. Conclusions

The LAES system has been receiving much attention as the realistic alternative as a grid-scale energy storage system. Options to integrate the baseload nuclear power plant already installed as part of the grid have been conceptually studied, and their potential to improve the overall performance of the integrated system will be further analyzed using cycle design tools in the future.

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