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Feasibility study of tightly coupled layout for nuclear integrated liquid air energy storage system

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1. Introduction

In 2013, NREL research team published the "duck-chart" which revealed considerable risk of overgeneration due to increasing generation of solar photovoltaics during the mid-day [1]. This phenomenon is pushing conventional power plant to reduce power generation with respect to the grid demand or to store energy in the form of mechanical, chemical, thermal and electrical energy.

A nuclear power plant is comparably more disadvantaged than other baseload sources to follow this trend. When a nuclear power plant operates under load-following operation, the reactor core and cladding integrity could be threatened because of varying core power.

To overcome these problems, an energy storage system (ESS) has been suggested and researched as one of the solutions for shifting the constant load of conventional nuclear power plants [2]. This trend implies the importance of research on applicable ESS for large grid scale energy storage.

For grid-scale ESS, three technologies can be considered: PHES (pumped hydro), CAES (compressed air energy storage), and LAES (liquid air energy storage). PHES and CAES have reached commercial and technical maturity, but have economical and geographical constraints [3]. However, LAES holds great potential because it has no geographical constraint, utilizes eco-friendly resources, presents high energy density and technical maturity. Therefore, in this study, LAES system is suggested for storing excess energy of nuclear plants

Nuclear integrated LAES has already been researched by Yulong Ding et. al [4]. The research team integrated the steam from the secondary side of the nuclear power plant with the discharging process to heat up the liquefied air. Additionally, excess electricity was used for compressor at the charging process. However, in the proposed layout, steam had to be bypassed during the discharging process, which led to a reduced power output from the nuclear plant.

However, in this study, newly integrated LAES is described which connects secondary side steam to oil charging process. This tightly coupled layout is expected to store excess energy in hot storage tank and generate additional electricity without steam bypassing at discharging process.

The purpose of this study is to evaluate the feasibility of newly integrated LAES with a nuclear power plant (NPP). Parameters such as round-trip efficiency and stored energy are calculated for assessing its performance using genetic algorithm and in-house code built in MATLAB environment.

2. Methodology

In this section, newly integrated LAES with NPP layout is described. The round-trip efficiency calculation method is suggested by the listed equations, and genetic algorithm is shown.

2.1 Nuclear integrated LAES Model

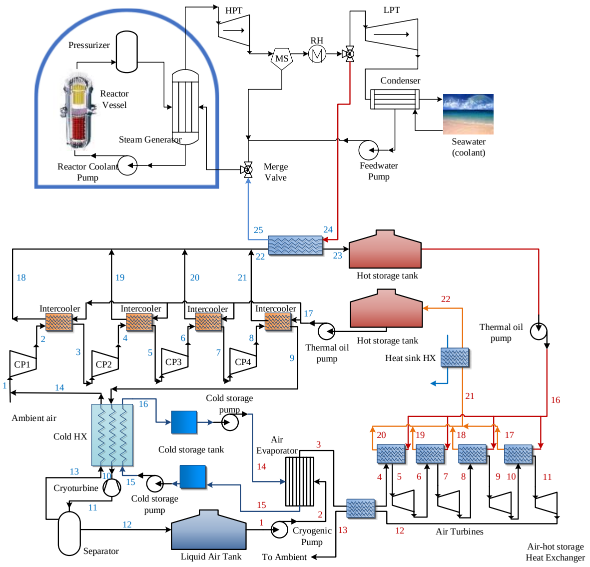

Fig. 1. Nuclear integrated LAES system configuration

Nuclear integrated LAES has basically three mode: charging mode, discharging mode, conventional mode. During charging mode, ambient air is compressed by four compressors (blue mark 1 to 9) and exchange compression heat to thermal oil (blue mark 17 to 21). High pressure cooled air is further cooled down by compressed air in the cold storage tank and stored in a liquid air tank (liquefaction). The new concept is that during overgeneration of electricity, secondary side steam is used to superheat the thermal oil. Excess energy is stored in the hot storage tank and condensed steam merges at the feedwater system.

During discharging mode, liquid air is pumped up and vaporized by compressed air in the cold storage tank. High pressure air is heated up by thermal oil in the hot storage tank (red mark 4 to 11) and generate electricity at four air turbines. When conventional operation mode, only nuclear power generates electricity without steam bypass and air liquefaction process.

2.2 Round trip efficiency calculation

Round trip efficiency is important indicator of ESS and is defined as the power output in the discharging cycle divided by the power input in the charging cycle.

$$\eta_{RT} = \frac{W_{discharging}}{W_{charging}} \tag{1}$$

where η_{RT} is round trip efficiency, $W_{discharging}$ is power output and $W_{charging}$ is power input. For charging power input, the following equations are used:

$$W_{comp} = \dot{m}_{air}((h_2 - h_1) + (h_4 - h_3) + (h_6 - h_5) + (h_8 - h_7))$$

$$W_{cryoturbine} = \dot{m}_{air}(h_{10} - h_{11})$$

$$W_{nuclear} = \dot{m}_{steam}(h_{24} - h_{23})\eta_{net}$$

$$W_{charging} = W_{comp} - W_{cryoturbine} + W_{nuclear} \tag{2-5}$$

where h_i is enthalpy at each position, $\dot{m}$ is mass flow rate and η_{net} is net efficiency of nuclear. $W_{nuclear}$ is calculated by using net efficiency of nuclear plant when considering same amount of heat is used in nuclear power plant. For discharging power output following equations are used:

$$W_{airtubine} = \dot{m}_{liq,air}\big((h_5 - h_6) + (h_7 - h_8) + (h_9 - h_{10}) + (h_{11} - h_{12})\big) \tag{6}$$

$$W_{pump} = \dot{m}_{liq,air}(h_2 - h_1) \tag{7}$$

$$W_{discharging} = W_{airturbine} - W_{pump} \tag{8}$$

Therefore, round trip efficiency is given by:

$$\eta_{RT} = \frac{W_{airturbine} - W_{pump}}{W_{comp} - W_{cryoturbine} + W_{nuclear}} \tag{9}$$

2.3 Optimization with genetic algorithm

LAES is a complex system among other ESSs. Many variables affect the system performance such as system maximum pressure, air & oil mass flow rate, cold storage box mass flow rate and temperature. Therefore, system performance cannot be compared for each parameter. In this study, genetic algorithm is used with eight variables for achieving the maximum round-trip efficiency (charging maximum pressure, discharging maximum pressure, air & oil mass flow rate, cold storage tank mass flow rate, inlet & outlet temperatures of storage tank, cold storage tank pressure). 100 variable sets and 100 generations are calculated. For each generation, 10% elite which shows the best round-trip efficiency in 100 sets are selected, 30% is crossover and 60% is deleted. Computation sets are given by:

Table I: Genetic algorithm computation sets

Properties	**Value**
Variable	8
Variable sets	100
Generation	100
Elite ratio	0.1
Crossover ratio	0.3
Deletion ratio	0.6

3. Results

3.1 Design parameters

For calculating the proposed system's performance, an in-house MATLAB code is used. Charging process runs until air inlet temperature converges to under error bound and discharging process runs until air outlet pressure converges to the same error bound. Air is used for main charging cycle and liquid air is used for discharging cycle. Thermal oil (VP-1) is used for hot storage tank. Steam mass flow rate is assumed as 20% of main feed water mass flow rate. For compressor section, each compressor has the same pressure ratio and the same mass flow rate for four intercoolers and air-hot exchangers. Other parameters are given at below table:

Table II: Design parameters

Properties	Value
$\dot{m}_{steam}$	445.41kg/sec
P_{steam}	1.39MPa
$T_{steam,in}$	524.65K
$T_{ambient.air}$	298.15K
$P_{ambient.air}$	101kPa
$T_{oil.in}$	298.15K
η_{net}	35.15%
$\eta_{air\ turbine}$	85%
$\eta_{cryo\ pump}$	70%
HX pinch temperature	10K
Pressure drop	1%

3.2 Optimized performance

Optimized results are listed in Table Ⅲ and Figure 2. The maximum achieved round-trip efficiency is 47.5% which is slightly lower than conventional LAES (~ 50%) and liquid yield is 81.4%.

Table III: Optimized results

Properties	Value
$\dot{m}_{air}$	2900kg/sec
$\dot{m}_{hotstorage}$	8174.8kg/sec

$\dot{m}_{coldstorage}$	2434.6kg/sec
$P_{max,charging}$	17.4MPa
$P_{max,discharging}$	9.8MPa
$T_{cold,in}$	91.2K
$T_{cold,out}$	299.6K
$P_{cold,in}$	11.2MPa
$Yield$	81.4%
η_{RTE}	47.5%

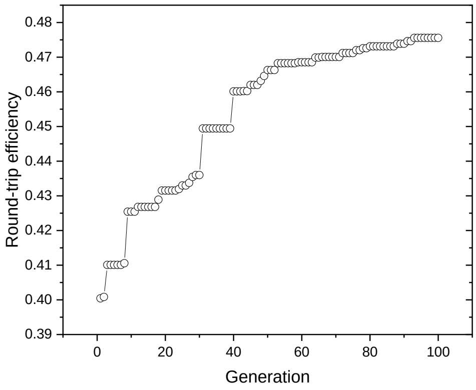

Fig. 2. Round-trip efficiency with respect to number of generations

Table IV: Net input & output power

	Charging input	Discharging output
LAES	1895.6MW	978.25MW
Nuclear	212.4MW	1402.0MW
LAES +Nuclear	2059.1MW	2380.3MW

For charging mode, compressor work is 1895.6MWe. Stored nuclear energy is 212.4MW corresponding to 15.05% of full power nuclear system. For discharging mode, net output power of NPP integrated LAES is 978.25MWe. However, net compressor work is calculated abnormally high. This is due to high compression ratio and high mass flow rate of air. For removing massive heat of steam, mass flow rate of thermal oil has to be high, consequently, mass flow rate of air is increased leading to practically impossible compressor work. To overcome this problem, mass flow rate of thermal oil has to be decreased. However, despite high mass flow rate of oil, heat of steam cannot be fully removed.

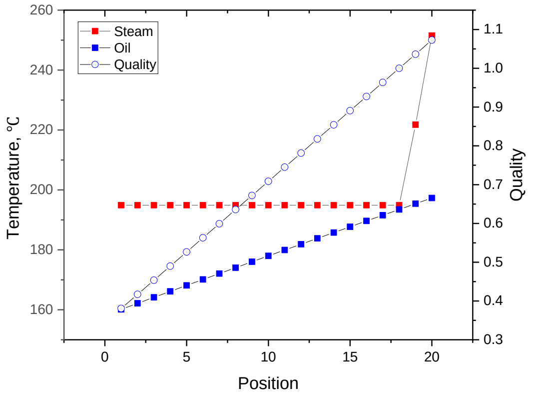

Fig. 3. Temperature and quality profile of steam-oil heat exchanger

Exit steam quality at steam-oil heat exchanger is still high because of low specific heat of thermal oil and pinch point problem located at phase changing point. Therefore, to achieve low mass flow rate of thermal oil and low steam quality at the same time, other heat transfer fluid can be used.

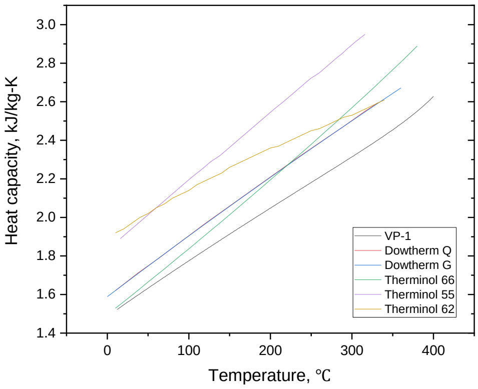

Fig. 4. Heat capacity of various thermal oil with temperature

VP-1 has the lowest heat capacity and Therminol-55 shows highest heat capacity among other thermal oil. Therefore, for removing heat of steam and decreasing mass flow rate of oil, Therminol-55 is most suitable material as long as material limitation allows. Another option is installing additional heat storage at steam-oil heat exchanger.

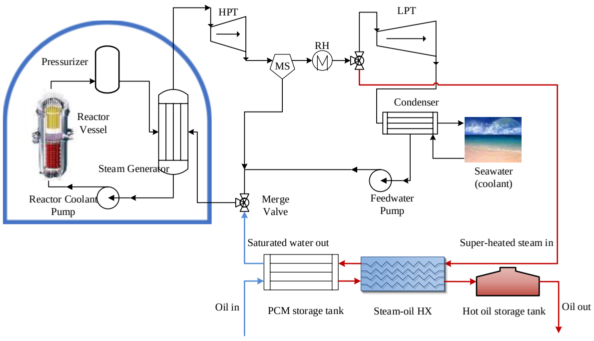

Fig. 5. Serial storage system configuration

The difference is that an additional PCM (Phase change material) storage tank is installed in front of steam-oil heat exchanger. First, excess energy of steam is stored in PCM tank. Stored energy is used to heat up thermal oil near steam saturation temperature. After PCM tank, thermal oil is superheated at steam-oil heat exchanger and stored in hot oil tank. Additional PCM storage tank is expected to show good synergy performance by absorbing latent heat of steam leading to low mass flow rate of oil. Also, PCM materials such as paraffin, sodium nitrate is much cheaper than thermal oil, therefore, total installation cost is expected to be decreased by using serial storage system.

4. Conclusions and further works

Performance of newly proposed NPP integrated LAES is studied by using in-house MATLAB code and genetic algorithm. Maximum achieved round-trip efficiency is 47.5% which is little lower than conventional LAES system and liquid yield is 81.4%. During charging mode, 15.05% of nuclear energy is storing at hot storage tank. At charging mode, net input power is calculated as 1822.8MWe. At the discharging mode, net output power is calculated as 978.2MWe.

However, there are still many practical problems and limitations to be solved. More specifically, net compressor work is too high not enough to afford in conventional power system. Also, exit steam quality of steam-oil heat exchanger is still higher than the saturation quality. Therefore, to reduce oil mass flow rate and exit steam quality, additional system options are needed. For further research, other thermal oil with higher specific heat such as therminol-55 should be considered and additional heat storage system can be used for storing excess steam energy further.

5. Acknowledgement

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