Evaluation of various large-scale energy storage technologies for flexible operation of existing pressurized water reactors

Jin Young Heoa, Jung Hwan Parka, Yong Jae Chaea, Seung Hwan Oh a, So Young Leea, Ju Yeon Lkea, Nirmal Gnanapragasamb, Jeong Ik Leea, *

a Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
b Canadian Nuclear Laboratories, Chalk River, Ontario, K0J 1J0, Canada

Abstract

The lack of plant-side energy storage analysis to support nuclear power plants (NPP), has setup this research endeavor to understand the characteristics and role of specific storage technologies and the integration to an NPP. The paper provides a qualitative review of a wide range of configurations for integrating the energy storage system (ESS) to an operating NPP with pressurized water reactor (PWR). The role of ESS technologies most suitable for large-scale storage are evaluated, including thermal energy storage, compressed gas energy storage, and liquid air energy storage. The methods of integration to the NPP steam cycle are introduced and categorized as electrical, mechanical, and thermal, with a review on developments in the integration of ESS with an operating PWR. By adopting simplified off-design modeling for the steam turbines and heat exchangers, the results show the performance of the PWR steam cycle changes with respect to steam bypass rate for thermal and mechanical storage integration options. Analysis of the integrated system characteristics of proposed concepts for three different ESS suggests that certain storage technologies could support steady operation of an NPP. After having reviewed what have been accomplished through the years, the research team presents a list of possible future works.

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1. Introduction

Many countries around the world have policies to reduce greenhouse gas emissions to combat the climate change. They have incorporated an expansion plan for clean energy with a focus on renewables and less emphasis on nuclear. These energy policies have been developed based on the COP21 Paris Agreement and have changed the energy market. The share of renewable energy, excluding large hydropower, has increased to 12.9% in 2018 in global power production, as many countries have invested heavily in solar and wind power [1].

When renewables, especially solar, increase their portion in the grid, electricity load imbalance issues are expected to arise. The California Independent System Operator (CAISO) published the duck curve, as shown in Fig. 1, which shows a significant decrease in the net load of the conventional power sources due to increasing solar photovoltaics (PV). It represents both the challenge of over-generation and need for high ramp rate mainly due to the solar penetration. The belly on the duck curve chart means when the demand of power other than solar (i.e. net load) is the lowest. In this graph, the belly shape grows gradually as the solar PV installation increases from 2012 to 2020 [2]. This is because solar PV generation has intermittent characteristics while the electricity demand does not follow the solar power generation curve. The net load curve, derived from subtracting the solar generation from the total generation graph, poses a heavy burden to the remaining power sources in the grid that must sharply increase or decrease output. Consequently, sudden output fluctuations may hinder the economics and stability of the baseload and conventional power plants such as nuclear.

Furthermore, the increase in renewable energy leads to the abrupt change in electricity price in the grid. According to the
report by FS-UNEP Collaborating Centre [1], it is shown that the wholesale energy prices fluctuate for scenarios under various shares of variable renewable energy (VRE). As the renewable portion expands in the grid, the price drops to nearly zero during high solar penetration and rises rapidly as the sun sets at demand peaking hours. To balance the uncertainties in the energy market demand and supply, auxiliary systems and services including energy storage systems (ESS) are required which add to the total cost of the energy transmission [3]. Under these conditions, providing flexible generators, along with reducing the need for baseload generators, are favored [4].

Contributing to 10% of global electricity supply in 2018 [5], nuclear power plants (NPPs) have primarily served as baseload sources because operating at rated power is generally more economical. However, with the grid demanding that the baseload players such as nuclear plants would reduce their load during daily peak renewable generation hours, there has been an increasing need to operate the existing nuclear plants flexibly. In order to reduce and increase the load of the nuclear fleets, one of the two methods can be selected: (i) controlling reactor power; and (ii) bypassing steam to a secondary system or venting it all together. According to the IAEA report, the first method involves introducing a flexible load-following operation by reactor control. To achieve this method requires modifications and approvals from regulatory bodies, aggravates the integrity of components by thermal and mechanical cycling, and adversely affects the economics if flexible services are not internalized into the grid system [6]. The first method has been adopted by several Member states of the IAEA by either incorporating the requirement into the new design or modifying the current design in operating NPPs.

On the other hand, the second method can potentially avoid some of these issues by operating the reactor at full thermal power and diverting the steam that is equivalent to the power not needed in the grid at the concerned time periods. The diverted steam could

### Nomenclature

<table>
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<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>CAISO</td>
<td>California Independent System Operator</td>
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<tr>
<td>PV</td>
<td>photovoltaic</td>
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<td>VRE</td>
<td>variable renewable energy</td>
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<td>ESS</td>
<td>energy storage system</td>
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<td>NPP</td>
<td>nuclear power plant</td>
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<td>PWR</td>
<td>pressurized water reactor</td>
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<tr>
<td>LNG</td>
<td>liquefied natural gas</td>
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<tr>
<td>STDC</td>
<td>steam turbine-driven-compressor</td>
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<td>HPT</td>
<td>high pressure turbine</td>
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<td>LPT</td>
<td>low pressure turbine</td>
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<td>MSR</td>
<td>moisture separator reheater</td>
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<td>CAES</td>
<td>compressed air energy storage</td>
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<td>CGES</td>
<td>compressed gas energy storage</td>
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<td>HES</td>
<td>hydrogen energy storage</td>
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<td>LAES</td>
<td>liquid air energy storage</td>
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<td>TES</td>
<td>thermal energy storage</td>
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<td>PHES</td>
<td>pumped hydro energy storage</td>
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<td>CCES</td>
<td>compressed CO2 energy storage</td>
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<tr>
<td>m</td>
<td>mass of storage medium</td>
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<tr>
<td>(c_p)</td>
<td>specific heat</td>
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<tr>
<td>T</td>
<td>temperature</td>
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<tr>
<td>(\epsilon)</td>
<td>effective number of transfer units</td>
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### Greek symbols

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<thead>
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<td>(\eta)</td>
<td>efficiency</td>
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### Subscripts

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<tr>
<td>(rt)</td>
<td>round-trip efficiency</td>
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<tr>
<td>h</td>
<td>hot side</td>
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<tr>
<td>c</td>
<td>cold side</td>
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*Fig. 1. The CAISO duck curve reported in the NREL report [2].*
either be vented or it can be accumulated into a storage system. Because nuclear power plants require high capital cost and low operation cost (due to low fuel costs), it becomes economically preferable to generate power at constant rate as baseload. Therefore, to prevent loss of revenue generation from the reduction of capacity factor, the existing NPPs can operate their nuclear reactor at full capacity when adopting the second method by storing the heat from the diverted steam during periods of low demand and to reuse the stored heat to generate additional power later during peak demand [7]. Another rationale for considering the second method is that the nuclear reactor now operates at full power at constant power rating, thereby avoiding changes relating to the safety and regulatory aspects. An efficient way to realize this is to couple ESS to the steam cycle on the secondary side of existing NPPs, using the available ESS technology options [8]. ESS can provide the auxiliary services of storing energy during overgeneration and generating additional power during peak demand, improving the profitability of the existing NPPs [9,10].

ESS can be integrated either to the plant directly known as behind-the-meter (BTM) storage (storage and control is at the power plant-level) or ESS can be integrated to the grid known as front-of-the-meter (FTM) storage (storage and control is at the grid).
grid-level), BTM energy storage technologies that involve thermomechanical energy conversion can be beneficial to operators when integrated with a nuclear power plant. The main advantage with BTM for NPPs is the direct integration with ESS such that the generated steam from the nuclear reactor can be more efficiently stored and discharged in the form of thermal or mechanical energy, to minimize conversion losses. Another advantage of this option, when compared to a direct integration of ESS with renewables, is that direct integration with nuclear power can avoid the off-design efficiency and component degradation issues due to the intermittent nature of the renewable input source. The BTM storage option with direct integration is technically an effective solution, a conceptual schematic is shown in Fig. 2.

The concept shown in Fig. 2 can be integrated not only to nuclear power plants but also to any large-scale thermal plants operating with steam or Rankine cycles, e.g. CCCT or concentrated solar power (CSP) plants, to augment their flexibility in the grid as players. Although various grid conditions such as the share of renewables and quick-response power plants for flexible power need to be considered to fully evaluate the conditions of the integrated system, the current work only considers the individual plant-level power balancing using ESS for existing PWR based NPPs. The information is derived through a review on the current status of ESS technologies suitable for BTM (behind-the-meter) integration with the existing NPPs in operation. The scope of interest is limited to existing plants, mainly operating pressurized water reactors (PWRs), or light water reactors (LWRs), because the review focuses on improving the performance of existing plant designs already connected to the grid, and thus, it leaves out the discussion of futuristic design concepts including Gen-IV reactors [8]. The analysis provides a comparison of available integration pathways and their characteristics for energy storage and power balancing behind-the-meter.

2. Energy storage system (ESS) options

Energy storage system (ESS), defined in this study, is characterized by its capability to store and release energy, with a period of idle time in between, all falling under a single operation cycle. Each ESS technology has its own advantages and drawbacks, and depending on the conditions under which it operates, the selection of the optimal technology can differ. It can also play various functions in the electric grid which are divided into mainly three categories: (i) energy management, (ii) power quality, and (iii) bridging power.

Because the focus of the study aims to review ESS technologies for operating PWRs, usually designed at a power capacity of 1000 MW range, the coupled ESS should target several hundred MW to store a portion of generated power from the NPP. The application area for the NPP integrated ESS options would thus be

energy management, which balances the power demand and supply between the NPP and the grid during certain hours in a day. The power balancing includes time shifting, peak shaving, and seasonal energy storage as specified categories of large-scale ESS functions [11].

The general concept of the plant-based storage integration to the operating PWRs works under three grid scenarios as illustrated in Fig. 3. Scenario 1 is when the grid does not suffer from peak demand or over-generation, baseload operation takes place with the operating PWR. Scenario 2 is when the grid encounters over-generation (or surplus), then within the NPP a portion of the steam flow (or power) from the PWR steam cycle is diverted to the ESS, thus undergoing the ‘charging mode’ to store surplus energy. Scenario 3 is when the grid is under peak demand, then the stored energy is released from the ESS to generate surplus power and fed to the grid directly, under the ‘discharging mode’.

Consideration is given to ESS technologies that take advantage of the direct integration with an operating NPP, it narrows down to three major types: (i) thermal energy storage, (ii) compressed gas energy storage (tank-based), and (iii) liquid air energy storage. The main rationale for the selection is that they can be installed as large-scale ESS without the geological constraints and that they do not suffer from AC-DC conversion loss and relevant transmission issues. For these reasons, the following ESS technologies are excluded in the scope of this review: hydrogen energy storage, battery energy storage, pumped hydro storage, and compressed air energy storage (cavern-based).

Lithium ion battery storage has been receiving attention as an alternative to grid-scale ESS, despite its limitations in terms of capacity and cost. Currently, the largest lithium ion battery farm built in the world is the 100MW/129 MWh Hornsdale Power Reserve farm built by Tesla and Neoen in South Australia [12]. The grid-scale lithium ion battery storage may increase in the future and will play a significant role in stabilizing the grid. However, the complementary role as a large-scale ESS playing the role of load-shifting and energy management in place of load-following operation of PWRs does not appear suitable for lithium-ion battery storage. Not only does the power level need to be increased several folds, but also the energy capacity needs expansion for several hours at the power level of several hundred MWs. For this reason, lithium-ion battery storage is not included in the scope of this study.

Hydrogen energy storage system (HES) also requires a quick discussion due to its prominence in the transport sector decarbonization and as an upcoming option for large-scale energy storage to support NPPs in the form of chemical energy storage [13]. Role of HES for NPPs was identified in a similar analysis by Idaho National Laboratory, but HES was ruled out due to its inability to perform energy arbitrage services and high costs [9]. There are also technological hurdles in the form of poor efficiencies and lack of commercial readiness at the scale of storage required for NPPs.

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**Fig. 4.** Charge-discharge cycle for energy storage using LAES.
There are usually two pathways for HES energy integration with NPPs: (i) electrical only and (ii) combination of thermal and electrical energy. The first HES pathway involves converting electricity to hydrogen (via water electrolysis process), storing it (in tanks or geologic caverns) and then re-converting it to electricity (via fuel cells). The round-trip efficiency of converting electricity to hydrogen to electricity (power-to-power) for the grid application has lower efficiency in the range of 20–30% [16], which is much lower than the power-to-power efficiency of thermal and mechanical storage options. The second HES pathway involves a combination of electrical and thermal energy integration of HES with an NPP with sufficiently high-temperature heat from the nuclear reactor and using a portion of the electricity from the grid or the NPP to produce hydrogen by splitting water. However, the relevant hydrogen production technologies for this option are yet to
be demonstrated, as these require the high-temperatures only available in advanced nuclear reactors that are also yet to be demonstrated [9,15].

Hydrogen storage requires not only the process of production but also requires the power generation via fuel cell, with the largest plant in the world at 50MWe planned in South Korea [17]. Under the same rationale for lithium-ion battery storage, hydrogen storage is not included in the scope of the study because its power and capacity as a large-scale ESS for PWR integration is not suitable. On top of this, large-scale ESS applications using hydrogen storage are known to have regulatory issues due to increased risk of explosion by hydrogen [18]. These reasons highlight in detail the reasons for excluding hydrogen storage in the review for PWR-ESS integration.

Hence, in this study, the large-scale ESS technologies evaluated for NPP integration are the following:

1) Thermal energy storage (TES)
2) Compressed gas energy storage (tank-based) (CGES)
3) Liquid air energy storage (LAES)

2.1. Thermal energy storage (TES)

Thermal energy storage (TES) is a technology storing energy in the form of heat energy. It has been initially studied and commercialized to complement the intermittency of the concentrated solar power (CSP) system, so the technology readiness level is relatively higher than other ESS technologies. CSP system utilizes the thermal energy from concentrated solar rays to generate a thermal-based conversion system, e.g. steam Rankine cycle, and to overcome solar intermittency, it adopts thermal energy storage for backup [19]. It becomes crucial to adopt the TES to an existing energy system for efficient and economical power generation. TES is an essential component that facilitates the balancing between energy supply and demand enhancing the performance and reliability of the integrated system. There are many active projects for
demonstration of the large-scale TES technology as well as commercial plants with a notable adoption in CSP plants, including Andasol solar power station in Spain and Nevada Solar One in the US [19,20]. In a TES, the thermal energy from the power plant is stored when there is oversupply due to low electricity prices, and thermal energy is released to generate electricity when there is demand in the grid [21]. One of the critical aspects of TES is the discharge temperature of the heat transfer fluid, since the thermal energy needs to be converted back into electricity when there is demand in the grid [21]. One of the critical aspects of TES is the discharge temperature of the heat transfer fluid, since the thermal energy needs to be converted back into electricity [22,23]. Here, exergy can be a useful concept, defined as the work producing potential of energy with reference to a reference environment [24]. If the thermal energy is at higher temperature, it would have higher exergy to be converted more efficiently to electricity. Three main types of TES exist depending on mechanism of energy storage — (i) sensible heat, (ii) latent heat, and (iii) thermochemical reaction.

Sensible heat storage involves storing thermal energy in various forms such as liquid or solid media (e.g. water, sand, molten salt, or rocks) by heating them using the heat transfer fluid [25]. This method is one of the most cost-effective among TES technologies [9] due to lower temperature differences between the storage medium and the surroundings. It is also the most commonly adopted technology among the TES candidates especially for large-scale CSP applications.

Latent heat storage uses materials that absorb and release latent heat through phase changes, called phase change material (PCM). For this method, the required volume of TES significantly decreases because of high energy storage density, and it poses the advantage of isothermal process enabling higher performance. Various candidates have been explored for latent heat storage, including organic materials such as paraffins and inorganic salts [26].

Thermochemical storage (TCS) utilizes the reversible thermochemical reactions during which thermal energy is released and absorbed. During the charging stage, reactant is heated up and forms products that are stored separately. During the discharging...
stage, the products react under designated conditions to release energy. Major advantages of thermochemical storage are high energy density (15 times of sensible heat storage) and its resilience to heat loss. Some examples of TCS utilize materials such as metal hydrides and inorganic carbonates undergoing reversible reactions [27].

Two indicators represent the performance of TES integrated to any power cycle - TES efficiency ($\eta_{\text{TES}}$) and round trip efficiency ($\eta_{\text{RT}}$). $\eta_{\text{TES}}$ can be defined as the ratio of the energy extracted from the storage medium to the energy stored in it, written as the following equation [28],

$$\eta_{\text{TES}} = \frac{m_{c}(T - T_{c})}{m_{c}(T_{h} - T_{c})}$$

where $m_{c}$ is the total heat capacity of the storage medium and $T$, $T_{c}$ are the hot and cold temperatures, respectively, of the storage during discharging. $T_{h}$ is the maximum temperature at the end of the charging period. This TES thermal-to-thermal efficiency reaches 97%, which means it can store thermal energy for long periods if tank insulation is designed properly to minimize self-discharge.

Because the primary purpose of TES in its integration with the electric grid is to provide electricity during discharging, it often requires a separate power cycle operating with the heat source from the TES. Therefore, the round-trip efficiency of TES connected to an electric grid is determined additionally by the efficiency of the power cycle, $\eta_{\text{cycle}}$, in the following equation.

$$\eta_{\text{RT}} = \eta_{\text{TES}} \cdot \eta_{\text{cycle}}$$

Since typical thermal power cycles perform at efficiencies of 30–60%, the overall round-trip efficiency for TES can range from 30 to 50% [28].

### 2.2. Compressed gas energy storage (CGES)

Another ESS technology applicable to NPP integration is compressed gas energy storage system (CGES). Here, this branch of ESS technology encompasses all compression-based energy storage, including air and CO$_2$. Only the tank-based types are considered in this paper since utilizing an underground natural cavern poses geological constraints on the ESS.

Commonly known as the compressed air energy storage (CAES), storage using compressed air has been researched ever since its first patent in the early 1940s [29]. CAES is a large-scale energy storage life, pump hydro energy storage (PHES), and commercially available. It operates by storing energy in the form of high pressure compressed air and generating electricity through air expansion. Two major projects of CAES include the 290MWe Huntorf plant in Germany built in 1978 and 110MWe McIntosh plant in Alabama, US built in 1991.

CAES can be categorized into three major types based on their idealized change of state during air compression process: diabatic, adiabatic, and isothermal [29]. For diabatic CAES, the heat from the compression of air is rejected to the ambient via intercoolers, and thus, an external heat source, e.g., gas combustion, is required in the discharging cycle. For adiabatic CAES, this heat of compression is captured by transferring it to additional TES tanks and is later utilized during the discharging cycle. In isothermal CAES, the heat of compression is minimized through the adoption of isothermal (or near-isothermal) compression schemes. The diabatic CAES projects have demonstrated round-trip efficiency of about 42–54% [30], and although no utility-scale adiabatic CAES plants are available, the pilot-scale demonstrations are estimated to reach between 63 and 74% [31].

Many of the studies and projects attempt to utilize an underground cavern to reduce cost and meet the design requirement of massive volume for the storage of compressed air. Recent progress for CAES with man-made tanks for compressed air storage has been made with pilot plant experiments [32,33], but most are investigated for small-scale applications. In Wang et al. (2016), it has been demonstrated that the average round trip efficiency of 22.6% has been attained for tank-based CAES. Nonetheless, CAES has been anticipated to be promising large-scale ESS technology due to its low cost and relatively high energy density.

Instead of using compressed air, energy can be stored using compressed CO$_2$, which is a storage medium receiving a lot of potential for the following reasons. Firstly, CO$_2$ has a critical point of 7.38 MPa and 30.98°C, which can be reached easily with currently available technologies [34]. Furthermore, supercritical CO$_2$ has high density and specific heat [35], and its utilization as a storage medium reduces its emission as a greenhouse gas [36]. By utilizing a storage medium with higher density, it can also raise the energy density of CGES compared to when air is used [37].

Even if the CO$_2$ resource may be abundant, the compressed CO$_2$ energy storage (CCES) adopts the closed cycle layout with storage tanks to prevent release and to avoid difficulties in supply [34]. CCES is divided into charging and discharging modes, during
charging mode the CO₂ from the storage tank passes through the compressor to be stored in the high pressure tank, and then during discharging mode, CO₂ flows through a turbine with the heat from thermal storage tank to improve the discharge energy conversion efficiency [38].

The operation types for CCES considered in this review are supercritical CCES (SC-CCES) and trans-critical CCES (TC-CCES). In the trans-critical operation of CCES, liquid CO₂ is stored in a low-pressure tank and heated in the preheater before it is compressed by the compressor. Then, supercritical CO₂ from the compressor is stored in high pressure storage. It has an advantage to ward off the large storage volume under the trans-critical operation. Since the low-pressure storage contains liquid CO₂, it has higher density than the gas or supercritical state, and the volume of the low pressure storage can be reduced [34].

CCES can also have various layouts such as diabatic and adiabatic modes. Diabatic CCES requires heat input from fossil fuel or other thermal energy source, while adiabatic CCES uses TES in storing heat recovered during compression or charging mode instead of thermal energy from external fuels such as natural gas or biofuels. In the supercritical operation of CCES, the phases of CO₂ at all points are supercritical. It does not need a preheater for heating from liquid to supercritical state in this operation, so it becomes simpler than the trans-critical operation.

2.3. Liquid Air Energy Storage System (LAES)

Liquid Air Energy Storage System (LAES) has received attention among the large-scale ESS technologies. The basic concept of LAES is similar to CAES in that it utilizes a compression and expansion scheme, but the main difference lies in the liquefaction process for air and the thermal storage in both charging and discharging modes. There are different layouts of LAES, but they share five common stages: compression, liquefaction, storing, evaporation, and expansion, as shown in Fig. 4.

When electricity price is low or generated power is over-supplied to grid, multiple air compressors are operated to compress purified air. Because air is compressed to nearly 180 bar, compressed air reaches high temperature. To recover this heat of compression, thermal storage system using materials such as thermal oil or packed bed is adopted. After air is compressed, air is additionally cooled down to around –196 °C by heat exchangers, and cold exergy is stored in cold storage fluids. After the liquefaction process, air is stored in the insulated liquid air tank. During the discharging mode, the cycle is operated reversely to the charging mode. Liquid air is pumped to ~120 bar and evaporated by storing its cold exergy in the cold storage fluids. After air is evaporated, air is heated by the stored thermal energy and expanded to ambient pressure by multiple air turbine stages. During the expansion stage, external heat sources such as LNG (liquefied natural gas) or waste heat can be used as well as the compression heat stored in thermal oil tank [39,40].

The major advantage of LAES over CGES is that it has 6–7 times higher energy density than that of CGES because energy is stored in the form of liquid state [41]. In addition, there is no need for an underground cavern or rock to store liquid air, since it only requires over-ground, insulated tanks [42]. Hence, LAES has potential to be integrated to the operating nuclear plants as a large-scale ESS.

Various studies have been conducted on the LAES concept and its applications. Kishimoto et al. proposed the first concept of LAES system [43]. Gucci et al. conducted the first extensive thermodynamic analysis of the stand-alone LAES system, reporting a calculated round-trip efficiency of 54% [44]. Sciacovelli et al. proposed LAES system with packed bed system and analyzed thermodynamic response which shows 50% round-trip efficiency [45]. Morgan et al. reported the first pilot-plant of LAES by applying Claude cycle
process [46]. To demonstrate the performance of LAES, Highview Power constructed a 350 kW/2.5 MWh scale pilot plant near London. Since 2018, Birmingham University has established a 5 MW/15 MWh scale pilot plant for further research, and performance test has been conducted in conjunction with gas power plants. However, round-trip efficiency of LAES is still lower than that of other ESS technologies such as PHES or CAES because of its large exergy destruction at the air liquefaction process [47]. To improve the efficiency of LAES, many studies are conducted by integrating LAES with other external power sources.

3. Literature reviews on ESS integration with existing NPPs

The section attempts to cover the available literature on integrating ESS technologies to operating PWRs. Because the investigation has been primarily conceptual, most of previous researches have evaluated the suggested layouts and options qualitatively, while some of them have analyzed thermodynamically albeit with...
simplifications. The paper also approaches the collective study on a macroscopic and descriptive level with a focus of categorizing the various options selected by the papers.


INL published a technical report reviewing various ESS
technologies suitable for integration to existing nuclear plants for enhancing their flexibility [9]. Several grid scenarios were considered in the study to formulate a macroscopic overview of what each ESS technology would require for the selected design criteria. Furthermore, the study reviewed possible options for state-of-the-art large-scale ESS technologies and assessed the characteristics of each one according to selected criteria, including performance and economics. According to the summarized output figure below (Fig. 5), the report concluded that pumped storage hydropower (PSH) or compressed air energy storage (CAES) would be two of the top recommended technologies by cost. However, the analysis did not incorporate details regarding how the integration can be realized, and detailed layout studies were not considered. In summary, the study performed by INL focused on providing a framework for selecting the energy storage technologies, rather than a perspective of examining the integration layouts on how to connect ESS to the PWR systems.

3.2. TES

Previous research regarding ESS integration with PWRs has mostly been conducted on TES technologies. This is perhaps because it is effective to directly store the massive energy generated from the PWR in the most available form of energy in the system. The heat from the nuclear plant can be stored in the TES and can be used to supply thermal energy to external systems that generate additional electricity. Mainly two types of nuclear integration with TES can be found and categorized. The first is with the primary side (from the nuclear reactor) and the second is with the secondary side (steam cycle).

3.2.1. TES integration with the primary side

The first category holds the reactor thermal output as constant while storing a portion of the available thermal energy in the TES before delivering the required heat to the main steam cycle. Denholm et al. suggested the conceptual layout for TES integration with the nuclear plant for load-following operation [48]. Here, the paper suggests that the integration option may pose operational issues regarding the reactor safety when the TES block is connected to the reactor core.

Edwards et al. (2016) proposed an integrated layout (Fig. 6) with an intermediate TES loop directly storing the nuclear thermal energy from the reactor to the TES storage tanks, and then releasing energy during peak demand [49]. The rationale behind storing the energy from the primary reactor coolant is that the losses due to heat transfer between the pressurized water of the primary loop and steam in the secondary side are one of the largest sources of exergy destruction in the system. However, in order to contain reactivity during accident conditions, a safety boundary using an intermediate loop of heat transfer fluid has been installed. Since modifying the existing NPPs in this manner will have practical issues regarding nuclear safety and licensing including stability of the thermal storage medium under radiation environment, this proposed design would be possible for new PWR designs rather than modifying the operating nuclear power plants.

3.2.2. TES integration with the secondary side

The second category also assumes that the primary side thermal power to be constant and bypasses a portion of the steam in the secondary side steam cycle to the TES to store thermal energy. The advantage of this option is that it can minimize the safety issues regarding the primary side. Most of the studies done on TES integration to operating PWR (or marked LWR in references) fall under this category, presumably because of regulatory considerations. It can be difficult to prove that the nuclear integration would be failsafe when TES is coupled close to the nuclear reactor, but since the secondary side is farther away from the regions relevant to nuclear safety, this method of integration can be more resilient in terms of safety.

3.2.2.1. NASA/EPRI/USDOE Report (1978). The project conducted by NASA, EPRI, and US Department of Energy reviewed a broad number of concepts for thermal energy storage most suitable for integrating to a 1140 MWe light water nuclear reactor [50]. Some of the candidates for TES technologies included steam accumulator, sensible thermal oil storage, packed beds, and phase change materials. For the points of steam extraction (steam bypass), the report considered HP turbine inlet, IP/LP turbine inlet, and feedwater heater outputs. The analysis was performed assuming 8 h of charging mode and 6 h of discharging mode for each day.

![Fig. 17. Schematic of mechanically integrated NPP.](image-url)
In terms of steam integration, there were two suggested methods (Fig. 7). First is the steam generation method, which uses TES to store heat during off-peak and to generate steam for operating a separate peaking turbine. Second is the feedwater heating method, which stores heat energy from feedwater heaters during off-peak and then to use the stored energy to reduce extraction thereby generating additional power during peak demand. The paper concluded that the feedwater heating system is the least expensive integration method for the LWR. For the TES technologies applied for the feedwater heating application, high temperature water storage using prestressed cast iron vessel (PCIV) and thermal oil storage with rock packed bed were recommended for economic feasibility and level of near-term deployment.

3.2.2.2. Forsberg et al. (2018). The research team led by Forsberg et al. (2018) at MIT conducted a collective study on coupling heat storage to light water reactors with steam cycles [7]. This study also included results from the collaborative workshop examining various ESS technologies applied to LWRs [10]. Also, referring from Denholm et al. (2012), the paper commented that in order to minimize production costs and operational challenges, the reactor should be operated at full power at all times [48]. Regarding the options of coupling heat storage to LWRs, the paper offered two: 1) stand-alone storage system that adopts a separate power generation system using bypass steam from the high-temperature turbine, and 2) added turbine production using stored energy from steam bypass. The paper highlighted the advantage of the second option requiring less capital cost than the first one.

Moreover, six classes of heat storage technologies, including steam accumulators and hot rock storage, have been described and examined. The paper described the concept of hot rock ESS, as described in Fig. 8, which uses crushed rocks with air ducts to heat air using a steam-to-air heat exchanger [51].

3.2.2.3. Amuda et al. (2020). Amuda et al. (2020) studied the TES integration system coupling the APR1400 (Korean PWR reactor) design and the TES [52]. As shown in Fig. 9, the process cycle for TES involves bypassing the steam from the high-pressure turbine (HPT) of the APR1400 steam cycle. Condensed steam is returned to the steam cycle after storage. From the Carnot efficiency perspective, extraction and storage as only considered using high pressure steam supplied directly from the steam generator. The analyzed recovery options are as follows: (1) recovered heat used to generate steam for injection to the hot reheat piping (2) recovered heat used to generate steam to replace extraction steam to high pressure feedwater heaters (3) recovered heat used for partial flow feedwater heating. Case 3 is selected as the optimized cycle based on the following criteria: (i) high round-trip efficiency (benchmarked at 80%) (ii) reduced MS extraction flow rate during the storage cycle (iii) improved heat transfer processes during heat recovery (smaller heat exchangers) (iv) simple hardware configuration with minor modifications to the existing plant structures, systems, and components (v) reduced oil flows (vi) reduced storage volumes.

3.2.2.4. Carlson et al. (2020). Carlson et al. (2020) studied the use of TES for flexible operation of NPP [53]. The research team suggested four TES integration options (Fig. 10): Steam is bypassed (1) at the outlet of the steam generator, (2) at the outlet of the HPT, (3) at the outlet of the moisture separator and fed in the condenser. These three options considered using a secondary cycle, in the form of simple Rankine cycle, to generate power when stored energy is discharged from the TES. For option (4), steam is heated by stored thermal energy of TES and enters the inlet of the LPT. Because steam is bypassed at the secondary side of NPP, there is no impact on the primary side of NPP. By modeling AP1000 steam cycle using turbine off-design methodology and TES power cycle, they compared these four options based on discharging efficiency, TES exergetic efficiency, capacity factor, and thermal efficiency of the power plant over a charge/discharge cycle. From the thermodynamic analysis,
option (3) shows the highest relative capacity factor and exergetic efficiency. The relative capacity factor and efficiency are 115% compared to baseload case. Option (4) has capacity factor and efficiency as much as 108% and has the smallest TES storage capacity. By representing various integration options between NPP and TES, the paper quantitatively presented the feasibility of TES integrated NPP.

3.3. CGES

In contrast to TES, the integration of CGES with existing nuclear power has not been much explored in the previous works. Only a handful of references can be listed as attempts for CGES integration, and even among them, the studies are not quantitatively detailed. Wattenburg (2018) provided with the concept and simple layout of integration, as shown in Fig. 11, between CAES and NPP [54]. In this paper, CAES is integrated with both primary and secondary sides of NPP, and each has a different purpose of integration. From the integration of primary side of NPP, the reactor pressure vessel (RPV) of NPP is connected to the cavern stored air of CAES, since the air can be injected directly into the RPV to expand and cool the nuclear fuel rods in an emergency. From the integration of secondary side of NPP, the design utilizes the enormous amount of waste heat from existing thermal power plants to replace natural gas used in existing CAES. In other words, the inlet air of the CAES discharging turbine is reheated from the steam of secondary side of NPP.

Rizwan-uddin (2019) briefly described a concept and schematic of CAES integration to existing NPP [55]. In this paper, CAES is integrated to secondary side of NPP thermally and electrically. Using thermal energy storage (TES), the air turbine inlet air is reheated by the heat energy of TES stored from the steam of secondary side. The electricity generated from the steam turbine generator from the NPP drives the air compressor of CAES.

3.4. LAES

There are many attempts to combine LAES with other power cycles, but detailed research or analysis on the integration with existing nuclear power plant is limited. Li et al. proposed novel...
Fig. 21. Schematic of LAES integration with PWR steam cycle.
4. Design summary and suggestions for PWR-ESS integration

The options of how the PWR-ESS integration can be designed are categorized according to the mechanism by which the energy from the PWR is transferred to the large-scale ESS. Largely, three ESS integration options are possible for the PWR layout — thermal, mechanical, and electrical, and it refers to the form of energy at which it is delivered from the PWR to the ESS. The former two methods of integration for PWR with the ESS involves the modification of the steam cycle in the secondary system of the NPP. The last option involving electrical integration can be an option for the PWR steam cycle, and it involves the partial use of its generated electrical energy as the input to the ESS. In this paper, a simplified steam cycle is designed to evaluate the possibility of integration with an ESS within a steam cycle of the PWR. Although previous evaluations on the thermal integration option of ESS to PWR systems have been performed extensively, they have not provided a bridging platform under which other methods of integration, as well as other ESS technologies, can be assessed together, especially in relation to the existing steam cycle of the PWR plant.

To compare the impact of the integration methods and layouts on the PWR steam cycle performance, the publicly available information from a reference PWR is taken as reference values for the steam power system [57]. This section attempts to evaluate the change in performance due to ESS integration from the perspective of the PWR steam cycle. Fig. 13 shows the design layout, and the conditions for the design cycle are listed in Table 1.

The steam flow diverted from the NPP steam cycle transfers energy to the ESS in the form of thermal or mechanical energy, and the transferred energy is stored inside the ESS. Even if some steam flow is diverted to the ESS, the feedwater temperature at the inlet of the steam generator must be kept constant. This is because a variation in feedwater temperature at the inlet of a steam generator result in a change in the reactor coolant temperature, which affects the reactor operation and its safety. Another important issue is where the steam flow diverges and where it returns back within the NPP steam cycle. This is because the branching point and the merging point determine the amount of stored energy and the output variation of the NPP. The high-pressure (HP) turbine inlet (No. 2 on Fig. 13) or the LP turbine inlet (No. 11 on Fig. 13) can be candidates for the branching point. Between these two options, selecting the branching point as the one before the low-pressure (LP) turbine in the steam cycle has the advantage of minimizing fluctuation of output to the nuclear reactor side. When a portion of the mass flow branches to the ESS, the LP turbine inlet flow decreases, and the output of the NPP decreases. Depending on the type of ESS, the ESS inlet conditions of the branch flow are determined.

Next, branching and merging points are specified to reduce pressure adjustment to meet the integration requirement. In the cycle layout where the branching and merging points are selected, the feedwater temperature on the inlet of the steam generator changes as the branch flow increases. Therefore, it is necessary to maintain feedwater temperature on the inlet of the steam generator by adjusting the extracted flow of the turbines. It should be considered whether the feedwater temperature can be maintained at the inlet of the steam generator by adjusting the extracted flow of the turbines according to the branching and merging points.

This section incorporates simplified modeling to obtain results of performance changes for the PWR steam cycle incurred due to ESS integration. They have been obtained by adopting off-design modeling for the steam turbines and heat exchangers. The turbine off-design model uses the methods from previous references [58,59], and the heat exchanger off-design model adopts the effective number of transfer units (e- NTU) method from known textbooks [60]. The mass flow rates of the steam turbine extraction lines have been adjusted so that the steam generator inlet results in the same temperature as the on-design value.

4.1. Thermal integration

Thermal energy storage (TES) system utilizes thermal heat as the energy carrier and stores the thermal energy from the bypass steam flow of the PWR steam cycle. As summarized in Carlson et al. (2019), the best storage option for thermal integration is using the steam bypass after the moisture separator reheater (MSR). However, because the steam pressure at the TES outlet still remains high even after storing heat, the options for merging point should be considered with respect to matching the suitable pressure point within the steam cycle.

Here, the performance change of the PWR steam cycle is evaluated with the thermal integration option of branching steam after the MSR and merging the flow by feeding back into the feedwater heater (point 57 in Fig. 14). When considering the heat exchange at the TES, heat is stored at maximum when the steam condition, entering at superheated vapor, exits at saturated liquid. Therefore, in this research, outlet enthalpy of steam at TES is assumed as saturated liquid enthalpy considering pressure drop.

Preliminary calculated results are provided in Fig. 15. It shows the change of steam cycle power, calculated as the percentage of reduced work from on-design work, with respect to steam branch fraction and transferred heat to TES. For clear comparison, a linear line is drawn representing an equal percentage point drop corresponding to the percent point of steam bypass. As the steam branch fraction increases, the work of LPT is linearly decreased while the work of HPT remains as on-design value. This is because the steam bypass in front of the LPT does not affect the HPT work but only LPT work.

The option of two-tank storage with an independent discharging cycle is displayed in Fig. 16. In the perspective of installing a TES dedicated power cycle, it has the advantage of ramping power at a faster and higher rate, independent from the large-sized steam cycle for the PWR.

4.2. Mechanical integration

Various ESS technologies use compressors to store electric energy by converting it into mechanical energy in the form of compressed gas. There has been significant development on large-scale electric motor, but most recently developed electric motor is only within 100 MW scale manufactured by Siemens [61]. Because this research is focusing on hundreds of MW class ESS, electric motor driven compressor has limitation to be implemented for the integrated ESS system in terms of technical and economic feasibility. To overcome the practical problem of the electric motor, steam turbine driven compressor (STDC) is presented. Siemens presents large-scale STDC for generator or mechanical drive for pumps and
compressors from 10 kW to 250 MW [62]. Therefore, STDC can be one of the most promising options for large-scale ESS using compressors.

As shown in Fig. 17, the location of STDC is selected as the place where the temperature and pressure points remain high while minimizing impact on the entire system. When steam is branched before LPT, work of HPT can be conserved while LPT is operated as off-design condition. Therefore, the STDC is located between second reheater and low-pressure turbine (LPT). This component is operated by the branched steam before LPT, and mechanical work is transformed into compression work with assumed mechanical loss. The expansion pressure of STDC can be assumed as the condenser pressure, the merging point having the lowest pressure in the system. For the option of branching steam before the LPT and merging the flow after the condenser, the performance change of the PWR steam cycle and the energy stored by the compressor are calculated.

Fig. 18 shows the change of power of HPT, LPT, and total work of STDC with steam branch fraction. As branch fraction of steam increases, the work of LPT is decreased slightly steeper than the linear. When compared to the thermal integration option, this result implies that there is greater impact on the steam cycle for the mechanical integration option. This is because the mass flow rate from the steam extraction after the HPT (point 41) is increased further as more exergy is extracted from the steam through the mechanical integration, in order to minimize the temperature change of the steam generator inlet.

However, when the two integration options are compared in the exergy perspective, as shown in Fig. 19, the exergy available from the steam bypass line is greater for the mechanical integration option. This is because the ineffective heat exchange between saturated (or near saturated) steam bypass line and the TES heat transfer fluid degrades the available exergy for the thermal integration option, whereas the mechanical integration extracts as much exergy from the steam bypass through a steam turbine. Hence, the two integration options should be evaluated considering both the power degradation of the PWR steam cycle and the available exergy transferable to the ESS.

Two ESS technologies are suitable for the mechanical integration option, CCES (Fig. 20) and LAES (Fig. 21). Firstly, the integration between PWR and CCES is established by adopting the STDC to operate the CO₂ compressor. However, this ESS technology can also utilize a thermal integration by storing thermal energy from the steam bypass to increase the temperature of the working fluid during discharging. Hence, CCES can adopt two methods to store energy: steam turbine driven compressor and TES from the bypassing steam. Consequently, the integration can be optimized as a combination of the two methods, thermal and mechanical.

The integration between the PWR and the LAES is established by mechanical driven steam turbine to operate hundreds of MW-scale air compressors. Because the realistic compressors (not isothermal) generate sufficient heat of compression, adding more heat energy to the system via steam bypass would not enhance the overall effectiveness of the storage. Therefore, it is suggested to integrate mechanically with the discharging cycle of the LAES rather than the discharging cycle with thermal integration.

4.3. Electrical integration

The electrical integration is classified under all methods of integration via electric grid connections. From the turbine generators in the PWR steam cycle, electrical energy, which is originally delivered to the grid, is stored in the integrated ESS in the form of the energy stored by the system. During the discharge mode, the energy should be transferred in the form of electricity (in the case of non-electrical ESS) to be sent off to the grid under the befitting requirements.

Because all ESS technologies are inherently compatible with electrical energy, this form of integration can be a default option. However, there are several circumstances under which it may not be technically feasible or desirable. Firstly, if the total load of electrical energy from the PWR cannot fully be managed handled by the converting device (e.g. turbomachine, thermal system) of the ESS charging system, this option may be viable. A situation may occur that a large-size compressor cannot be operated by an electric motor and thus may require a mechanical drive instead, which is explained in more detail in the next section. Secondly, if the conversion of the electrical energy to other forms of energy compatible with the ESS becomes significantly costly or inefficient, other integration methods can be considered. For the case of thermal storage, the electrical-to-thermal conversion may be less efficient than the direct thermal storage.

5. Summary and future works

The analysis provided in this article covers a range of options for integrating the ESS system to an operating PWR-based nuclear power plant. The analysis is based on a literature survey and a qualitative assessment of proposed integration options. The integrated system characteristics of three proposed concepts are assessed using the off-design modeling for the PWR steam cycle when thermal and mechanical integration options are adopted. Thermal integration has been identified to have less impact on the LPT work reduction than mechanical integration, but the available exergy is greater for the mechanical integration option. The qualitative design suggestions for PWR-ESS integration options are suggested for the three large-scale ESS candidates assessed — TES, CCES, and LAES.

The current research still remains at a conceptual and qualitative level, providing the background on which further in-depth analysis can be performed in the future. Based on the learnings from this analysis, some future works could include:

- Perform economic assessment of various grid energy supply-demand circumstances presented by the recent rise in renewable energy generators.
- For direct coupled integration options with the secondary side, safety and regulatory review needs to be conducted to ensure that there would be minimal impact to the continued operation of the NPP.
- Detailed analysis needs to be performed to assess the ramp rate of the integrated system, as it undergoes the mode transition from normal operation to charging or discharging operation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Research Foundation of Korea grant funded by the Korea government (MSIP) (2019M2D2A1A02059823).

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