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Review article

Thermal energy storage integration with nuclear power: A critical review

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ABSTRACT

The increasing adoption of intermittent power from renewable sources necessitates enhanced flexibility from conventional power plants. This is essential to accommodate the fluctuating output of renewable sources while ensuring the security of the energy supply. In the present scenario, the integration of thermal energy storage systems (TES) with nuclear reactors holds the potential to enhance the uninterrupted and efficient functioning of nuclear power plants. However, TES systems face major barriers to investment since more knowledge of their systems' compatibility and performance indicators is needed to assess their benefits and the challenges associated with their integration with Nuclear Power Plants (NPP). The study provides a comprehensive overview of the advancements made in the domain of NPP for TES integration. Moreover, the present literature effectively elucidates the outcomes and challenges associated with the advancement of nuclear/TES technologies. This study also examines several investigations on hybrid nuclear/TES systems, which involve the integration of renewable and nuclear energy sources with TES. These investigations emphasize the approach of maximizing the utilization of renewable sources and improving their practicality. Significant advancements have been observed with the integration of Energy storage systems (ESS) with NPP (or hybrid NPPs). These improvements include several kinds of benefits, such as increased flexibility, enhanced overall efficiency, improved safety, and increased cost-effectiveness.

1. Introduction

The escalating demands of thermal energy generation impose significant burdens, resulting in resource depletion and ongoing environmental damage due to harmful emissions [1]. In the present era, the effective use of alternative energy sources, including nuclear and renewable energy, has become imperative in order to reduce the consumption of fossil fuels as well as the release of carbon dioxide and other greenhouse gases [2]. Most renewable resources, such as wind, solar, geothermal, and ocean energy, face issues related to intermittent availability, limited cost-effectiveness, and infrastructure complexities, especially when it comes to large scale production and distribution. The life cycle assessment does not currently support the preference for some of renewable energy sources due to the greenhouse gas emissions associated with their development [3]. The present era necessitates the development of energy production methods that can effectively address these factors or synergistically integrate with renewable energy sources to offset these challenges [4].

Nuclear power plants (NPPs) have emerged as a feasible means of attaining environmentally sustainable energy, cost efficiency, and uninterrupted power supply, among other benefits [5]. Nevertheless, it is important to acknowledge that every technological advancement is not without its limitations. In the case of NPPs, safety concerns emerge as a prominent issue that demands significant attention. Moreover, the variability in electricity demand exacerbates the safety concerns associated with NPPs [6]. Energy storage systems (ESS) that are integrated with nuclear power plants (NPP) serve multiple purposes. They not only store excess energy generated during off-peak periods but also effectively manage fluctuating energy demand and mitigate safety concerns. Integrated ESS nuclear power plant yields a higher capacity factor. Various forms of energy storage systems are currently under development, including mechanical energy storage (MES) systems, thermal energy storage (TES) systems, electric energy storage (EES) systems, and chemical energy storage (CES) systems [7]. In addition, the integration/merging point and overall effectiveness of these ESS are of utmost

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Nomenclature

ABWR	Advanced boiling water reactor
ACP-1000	Advanced China pressurized (SMR) reactor
AP1000, APR1400	Advanced pressure reactor
BWR	Boiling water reactor
CAES	Compressed air energy storage
CES	Chemical energy storage
DHC	District heating and cooling
EES	Electric energy storage
EPR	European pressurized reactor
ESBWR	Economic Simplified boiling water reactor
GCR	Gas cooled reactor
GFR	Gas-cooled fast reactor
LFR	Lead-cooled fast reactor
LWGR	Light water gas-cooled reactor
MED-TVC	Multi-effect desalination having thermos-vapor compression
MES	Mechanical energy storage
MSF	Multi-stage filtration
MSR	Molten sale reactor
PHWR	Pressurized heavy water reactor
PWR	Pressurized water reactor
RO	Reverse osmosis
SCWR	Super critical water reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
TES	Thermal energy storage
VHTR	Very high temperature reactor
VVER, VVER-1200	Water-water energy reactor

importance for the purpose of achieving optimal efficiency and mitigating safety concerns [8,9]. Numerous investigations have provided evidence of the hybrid integration of ESS, specifically the combination of renewable energy systems with NPP and ESS. This integration aims to optimize the efficiency of renewable energy sources and reduce their dependence on intermittent temporal patterns [10].

In the past both experimental and numerical methods have been used to study the integration of ESS and NPP. However, numerical methods have received far more attention than experimental methods [11]. The majority of studies in literature address several critical parameters, including the optimal fraction of input energy for ESS, the charging and discharging time, the roundtrip efficiency, the mitigation of safety load, the overall efficiency of the plant, and the increase in cost per kilowatt-hour (kWh) [12,13]. Thermal and mechanical energy storage systems are generally considered the most reliable and economically efficient options among the various types of ESS for NPP [14]. These systems offer higher capacity factors and overall efficiency. Ibrahim et al. [7] and Zakeri and Syri [15] compared the efficiency and cost per kWh of various ESS, including pumped hydro, compressed air, and sensible heat. The most efficient of these was found to be pumped hydro, followed by sensible heat and then compressed air. They concluded that the cost of these technologies is highly dependent on their scale. Nevertheless, the utilization of sensible heat does not require the inclusion of an additional turbine, unlike the extraction of power from pumped hydro. On the other hand, compressed air storage requires the implementation of supplementary components, such as hydro- and aero-turbines, to facilitate the process.

It has been acknowledged that there is global literature on NPPs, their characteristics, and the integration approach with ESS, but these studies have not been compiled into a comprehensive review to the best of author's knowledge. Furthermore, this paper not only provides a more comprehensive analysis of the novel strategies used for the integration of ESS with NPPs but also provides an in-depth exploration of the associated challenges and concerns. The primary emphasis is placed on TES systems, particularly those utilizing latent and sensible heat storage, as well as the different types of TES materials, specifically phase change materials (PCMs). The current review holds significant value when performing a literature survey aimed at evaluating the present status of ESS technology in NPPs and identifying any areas that require attention for the purpose of improving these systems. [16]. To the authors best of knowledge no such review exists in the literature.

The present study consists of six sections. Section 1 (Introduction) serves as a preliminary statement in this review article. Section 2 (TES systems for NPPs) of this study encompasses an extensive review of the existing literature pertaining to several TES technologies and their integration with NPPs. Section 3 (ESS integration approaches) provides a concise overview of the integration methodologies related to ESS in NPP while also outlining the obstacles associated with the integration process. The fourth section (Future prospective and trends) of this study clarifies the future prospects and trends pertaining to nuclear/TES plants. Section 5 (Future recommendations) delves into the discussion of future recommendations subsequent to the identification of research gaps. Section 6 (Conclusion) concludes the current study and serves as the final segment.

1.1. Nuclear power plants

Nuclear technology contributes to around 2635 TWh of electric capacity which is 10 % of the total electricity demand of the world [17]. Almost 100 more NPP (with a total capacity of 8730 TWh) are in the design, manufacturing or planning phase to be completed by 2030 with an additional 300 more plants proposed [18]. These states show that nuclear energy is a fast-growing technology for electricity generation and it is estimated that by 2050 it will become the most contributing technology in carbon-free energy generation [19]. In light of this, continuous research is being directed towards developing novel and hybrid systems; NPP coupled with renewable sources to achieve safe and seamless energy production [20].

Nuclear reactors can be classified either based on their configuration or by their generation level. In the first category, there are two most common reactors, fast reactors and thermal reactors. The first type, known as fast reactors, because they produce more fissile material than they consume. Conversely, within the category of thermal reactors, various configurations of moderators, responsible for controlling neutron energy, and coolants are used. This facilitates the transfer of heat produced within the reactor; many such reactors have been effectively developed and deployed [13].

The evolution of nuclear reactors can be categorized into four generations. The first-generation reactors (PWR, BWR, GCR, PHWR, LWGR, etc.) were developed in the mid-20th century and mostly lacked structural safeguards and passive safety features. The second-generation reactors (PWR, VVER, PHWR, BWR, etc.), developed in the 1970s, incorporated decent safety features but still had limitations. The third-generation reactors (AP1000, EPR, ACP-1000, VVER-1200 SMR, ABWR, ESBWR, etc.), established from the 21st century onwards, feature advanced structural safeguards and/or passive safety features. Finally, the fourth-generation reactors (GFR, LFR, MSR, SFR, VHTR, SCWR, etc.) are highly efficient and incorporate advanced safety features, resulting in minimal production of spent nuclear fuel. These reactors are considered to be the reactors of the future [13,21].

1.2. Energy storage system

The current review focuses on the energy storage systems compatible for nuclear reactors. Currently, for this purpose, thermal energy storage systems are well studied due to higher conversion efficiency and require less modifications [22,23].

1.2.1. Mechanical energy storage systems

Energy can be stored in a mechanical system by using either kinetic or gravitational forces. Despite the apparent simplicity of mechanical systems (for example, spinning a flywheel, or lift weights up a hill), the technology that makes utilization of MES is highly advanced [23]. Steinmann [24] considered thermo-mechanical concepts for bulk energy storage. Zhou et al. [25] reviewed thermal energy storage in compressed air energy storage systems. In another study [26], the primary objective was to address the issue of energy losses resulting from heat compression by proposing novel concepts such as coupled CAES air-cycle cooling and heating systems (isothermal, adiabatic and micros) as well as constant-pressure CAES coupled with pumped hydro storage. An isothermal CAES system uses heat transfer to minimize compression work and maximize expansion work without fuel or high-temperature thermal storage where as an adiabatic CAES system stores a large part of exergy as thermal energy utilizing it for expansion. On the other hand, a micro-CAES system with air cycle cooling and heating can be an effective distributed power network system since it stores energy, and generates electricity from multiple heat sources. [27] reported that a constant-pressure CAES and pumped hydro storage decreases the expansion throttling.

1.2.2. Chemical and electrical storage systems

There are also few studies which demonstrate the chemical and electrical storage energy integration with NPPs. For example, Revankar [28] discussed six methods of nuclear-based production of hydrogen fuel to store surplus energy as chemical energy storage which included 1) low-temperature electrolysis, 2) high-temperature electrolysis, 3) steam reforming, 4) thermochemical decomposition of water, 5) carbon, hydrocarbon and biomass conversion, and 6) radiolysis of water. This study has highlighted safety concerns regarding the integration of a hydrogen production facility with a particular NPP. It suggests that to prevent the spread of accidents between the two plants, either a sufficient separation distance or a suitable physical barrier should be implemented. In addition, several other supplementary components are necessary for this integration, including storage and processing capabilities for hydrogen. Chen et al. [29] suggested implementing battery energy storage along with a nuclear power plant (NPP) in order to solve the problem of grid stability. An economic analysis was performed to determine the most cost-effective battery type and construction scale, taking into account the overall economic benefits of integrated operation within the load factor limit. Comparative analysis reveals that the lithium iron phosphate battery energy storage with capacity of 270 MW demonstrates the highest and most consistent overall performance in terms of the internal rate of return (IRR), payback period (PBP), and levelized cost of electricity (LCOE), which were found to be 16.27 %, 6.27 years, and 0.064 $/kWh, respectively.

1.2.3. Thermal energy storage systems

Thermal energy storage involves cooling or heating a medium in order to use the energy later. A classic example of TES is storage of hot or cold water in an insulated tank to manage peak district heating and cooling. TES is commonly employed to balance the peak (daytime) and off-peak (mid-night) energy demands [30,31]. TES systems can comprise of several technologies based on energy storage duration requirement; thermal energy may be stored up to several hours, days or even months. A TES can be classified either based on the working principle (active/passive type) or energy storage technology (sensible, latent and/or thermochemical). In an active TES system, heat is not directly stored in the working HTF, however, in a passive system, HTF is stored in separate tanks [32–34].

According to the second classification, TES systems are divided into three basic types: sensible heat, latent heat and thermochemical. Sensible thermal energy storage is generally accepted as the most practical approach to lowering energy use and CO_2 emissions [30,31]. It can typically be accomplished by storing heat energy in water and then extracting it when necessary. The most common use for this type of TES is found in residential buildings [35,36]. Systems for storing latent heat rely on a medium's transition state rather than its temperature to store energy. It has proven possible to produce materials known as ‘phase change materials (PCM)’ that can store heat as latent heat in their mass. These substances are frequently utilized in building materials and solar applications, where they absorb and store extra building heat. Recently, researchers have concentrated on developing the latent heat storage system for NPP [37]. Lastly, thermochemical heat storage systems, which are based on chemical reactions.

Due to the fact that heat accounts for 50 % of global final energy consumption (International Energy Agency, 2013), TES will be crucial in the future energy systems both to mitigate intermittent renewable energy sources and to regulate the usage for NPP according to demand. TES systems are considered reasonably cost-effective, and some are also environmentally green compared to other storage systems [38]. Heating and cooling networks (DHC) can benefit from TES in a number of ways, including reduced peak thermal demands, improved system efficiency, and integration of additional heat sources like seawater or industrial waste heat [39].

2. TES systems for NPP

Thermal energy storage systems provide important benefits in nuclear power plants by enabling load balancing, enhancing grid stability, improving efficiency, providing backup power, and optimizing costs. As the energy landscape evolves, these systems can play a crucial role in integrating nuclear powers with other renewable energy sources and ensuring a reliable and sustainable electricity supply [40,41]. TES technologies function by harnessing and later releasing energy through the control of temperature, typically involving the heating, cooling, melting, and/or solidification of a storage medium. This stored energy can then be utilized for diverse applications by effectively reversing the process. When combined with NPPs, TES technologies have the capability to retain any surplus energy, which is not utilized for electricity generation, in the form of heat [42].

2.1. Purpose of plants

Thermal energy storage (TES) systems integrated with NPP improve energy consumption. The TES technology optimizes a nuclear power stations' load by storing excess thermal energy during low electricity demand periods. Sadeghi [43] presents a comprehensive review of the thermal energy storage development and integration challenges with power generation. The system can release this stored energy during peak demands, lowering the requirement for an alternative power generation system. During peak demand or nuclear plant outages, the TES system uses stored thermal energy to stabilize the grid [44]. When fully charged, the TES system can supply additional power to the grid, which helps to address the issue of delayed load response in nuclear power reactors. TES integrates extra thermal energy and releases it during abrupt load fluctuations to improve power supply flexibility and system stability. In critical situations, TES systems provide backup power supply by utilizing stored thermal energy for electricity generation through methods like steam turbines or heat engines. Several researches have demonstrated that TES systems can be employed as a cooling system of reactor during peak hours [45,46]. Moreover, TES can contribute to district heating and cooling applications by utilizing the excess heat generated by the nuclear power plant and distributing it to nearby residential or commercial areas [23] and [47].

2.2. Hybrid energy plants

A hybrid energy plant is broadly known as one which has two or more technologies merged. For the current study, a nuclear power plant coupled with renewable energy technology (wind, solar, geothermal etc.) to ensure the maximum utilization of renewable energy and increase in its efficiency, can be considered as a hybrid system. When employing hybrid systems to generate power, there are several factors to take into account as such these systems must be economically feasible and eco-friendly especially when used in off-grid rural areas [48]. A traditional example of a hybrid system is a photovoltaic-diesel hybrid system, where PV panels are unable to provide electricity, the diesel system kicks in to meet the electricity demand [49].

In an effort to maximize the use of extra energy (during off-peak hours), desalination plants have also been coupled with NPPs in the past. For instance, researchers have experimented with using NPP's waste heat and steam for thermal desalination. Al-Othman et al. [50] assessed the effectiveness of the multi-stage filtration (MSF) and reverse osmosis (RO) plant coupled with nuclear waste heat. Similarly, Sadeghi et al. [51] performed a techno-economic analysis of several thermal desalination facilities using excess/waste heat from a NPP. One of their major conclusions was that hybrid desalination can be considered as a suitable technology to reduce the overall cost of water, particularly in regions where there is high water demand. Dong et al. [52] proposed the flexible control system which is capable of handling coupled nuclear and renewable sources with thermal desalination (multi-effect desalination thermal vapor compression). The primary challenge of stable functioning of the grid was presented by this system, which was the primary focus of their research. This is also a constraint of the present investigation, where the grid frequency experiences a rapid increase, there is a resultant decrease in the electric load. In this situation, the primary steam regulating valve reduces the flow rate of the primary steam, leading to an increase in the primary steam pressure, thereby indicating an imbalance between heat generation and consumption. The primary function of the steam pressure stabilizer is to regulate the nozzle cross-sectional area of the steam ejector at the inlet of each MED-TVC (multi-effect desalination having thermos-vapor compression) module. When the electric load increases, the frequency experiences a rapid reduction, necessitating the activation of a frequency stabilizer to initiate the opening of the main steam regulating valve in order to ensure power balance. The function of the pressure stabilizer is to regulate the thermal balance by reducing the cross-sectional area of the steam ejector nozzle in response to an increase in the main steam flowrate.

For this study, hybridization means the combining of NPP and renewable source along with TES. For example, Borisova et al. [53] proposed the idea of integration solar photovoltaic system with NuScale SMR plant along with TES. For this setup, solar photovoltaic serves the purpose of superheating molten salt which is then used for heating the steam generator of the nuclear reactor (as shown in Fig. 1). This study investigated three different ESS models, which significantly improved overall efficiency by maintaining the high-capacity factor of nuclear power generation. Findings concluded that large size TES are more economically beneficial i.e., compressed air and hydro pumped storage cost 4400 USD per kWh while sensible storage with capacity of 32,965 kWh (15–18 h) of energy costs only 761 USD per kWh. Hybridization has also proved to be cost effective such as electricity cost for 1 kWh was found to be 348 and 433 USD per kWh with and without solar photovoltaic sources, respectively.

A numerical study was conducted by Zhao et al. [54] on hybridization of concentrated solar power (CSP) with nuclear power along with TES (molten-salt packed bed) (as shown in Fig. 2). They used values of real time demand for 7 days to evaluate the performance of the system. Additionally, a parametric study was conducted by the researchers, which revealed that a smaller heliostat field combined with a TES system was capable of higher utilization of heat generation. Conversely, a larger heliostat field combined with a higher capacity of NPP-TES system led to higher power supply efficiency. However, optimal values were found to be 50 % proportion of nuclear power capacity with 14.8 h storage capacity of TES and 1.27 times of heliostats field than solar panels. Sensitivity analysis revealed that when nuclear power generation increased, utilization of heat generation decreased and there was a rise in the discordance between CSP and TES. Furthermore, development of TES according to optimized value (14.8) requires 23.5 m radius tank which is not currently practical, therefore, two tank configuration with 20.9 m does the same job.

Hovsapian et al. [55] performed dynamic modeling on their proposed conceptual design (grid-scale ternary-Pumped Thermal Energy Storage system) to make use of a hybrid renewable/NPP flexible system (Fig. 3). Nuclear Flexibility Enabler was used to handle the load variation by switching instantaneously from extracting stored energy to storing excess energy and vice versa according to demand. Three operation modes were developed in this study including 1) nuclear energy to heat pump to TES, 2) TES to heat engine to grid and 3) direct conversion (nuclear energy to TES when heat tank is completely charged). Real-time data was considered for the simulations which showed that for achieving maximum output, very swift response times (1–30 s) for heating coil and heat pump were needed. The proposed design also had the capability to operate solely on NPP in case of low or no renewable source availability.

Another investigation was conducted by Bayomy and Moore [56] that examined the nuclear/TES system along with the solar plant (CSP) from a technical and economic perspective for heating and electricity

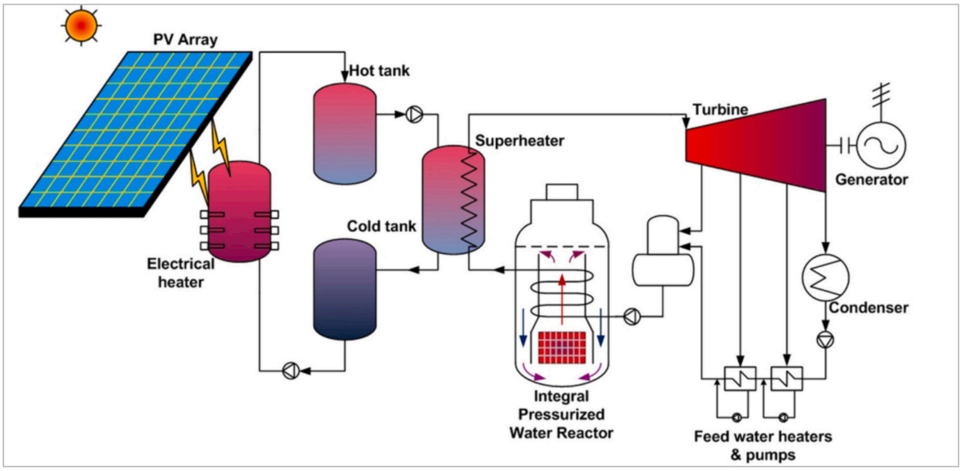


Fig. 1. Schematic of nuclear/TES plant, proposed by Borisova et al. [53] (adapted with permission from reference [53], copyright 2016 Elsevier B.V.).

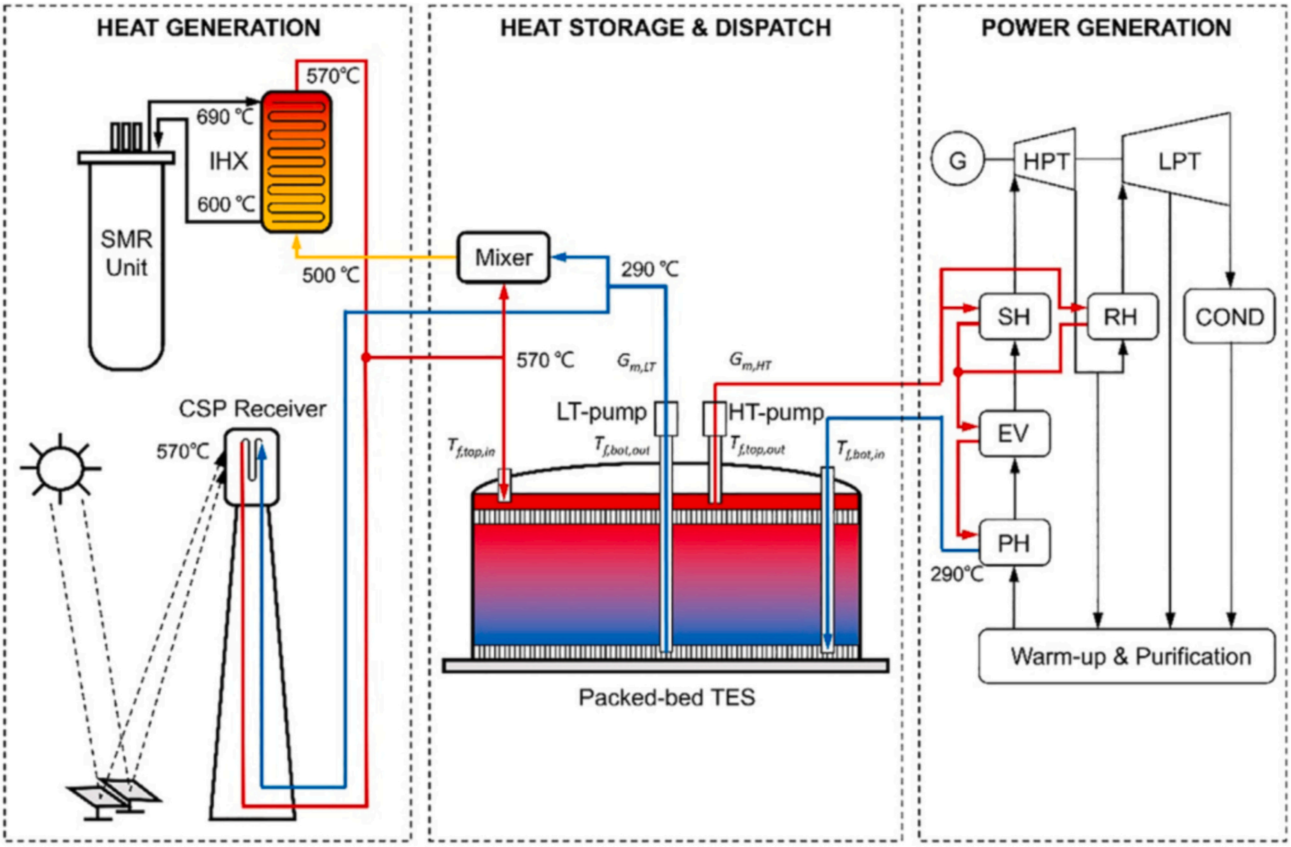


Fig. 2. A diagrammatic representation of the hybrid nuclear/TES plant with solar, reported by Zhao et al. [54] (adapted with permission from reference [54], copyright 2018 Elsevier B.V.).

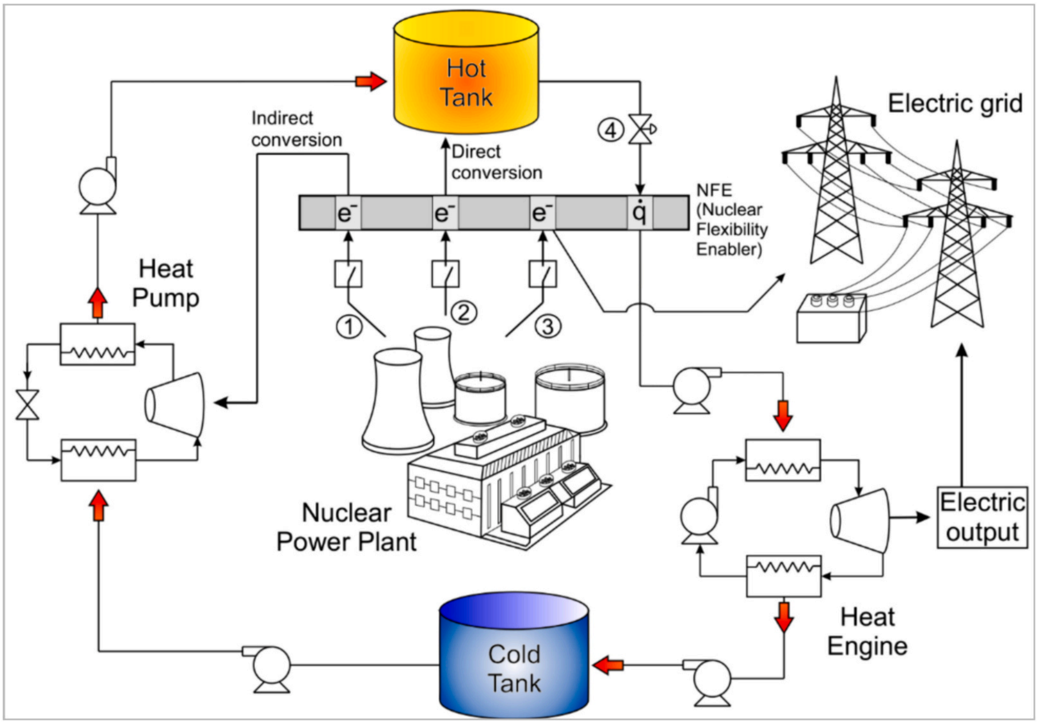


Fig. 3. Graphical representation of the layout of nuclear/TES system with renewable source and grid connection, presented by Hovsapian et al. [55] (adapted with permission from reference [55] copyright 2021 MDPI).

demand. The comparison of 5 different thermal storage fluids (Therminol, Downtherm, solar salt, Hitec salt and Hitec XL salt) was also one of the key objectives in this study. Based on the specific electrical load, Therminol was found to be the most viable candidate as the thermal storage fluid. They concluded that the capacity of the renewable resource and the TES significantly affect the cost-effectiveness as well as the thermal load of the NPP (Fig. 4).

Denholm et al. [57] analyzed the various combinations of wind and solar renewable sources with nuclear/TES by varying the proportion of these sources. In two cases, 50 and 60 % of the energy came from renewable sources, with the remaining energy coming from nuclear and TES. For the further subcases the amounts of renewable sources varied for wind, PV, and CSP, were 60–65 %, 20–25 %, and 15 %, respectively. Findings revealed that while a higher proportion of renewable energy sources allowed storing more energy, it also involved the development of more advanced load-shifting systems and larger TES, which raised the capital costs.

A grid that relies heavily on wind and solar power necessitates a highly adaptable system balance in order to accommodate the unpredicted variability of the net demand. The implementation of conventional nuclear power is hindered by both technical challenges associated with plant cycling and economic constraints caused by reduced capacity factors. A viable approach involves combining thermal energy storage with nuclear power plants. Because of this, the reactor's output could be kept at a practically constant level while the electrical generator's output can be varied in response to the changing demands of the net load [58].

2.3. Types of TES systems

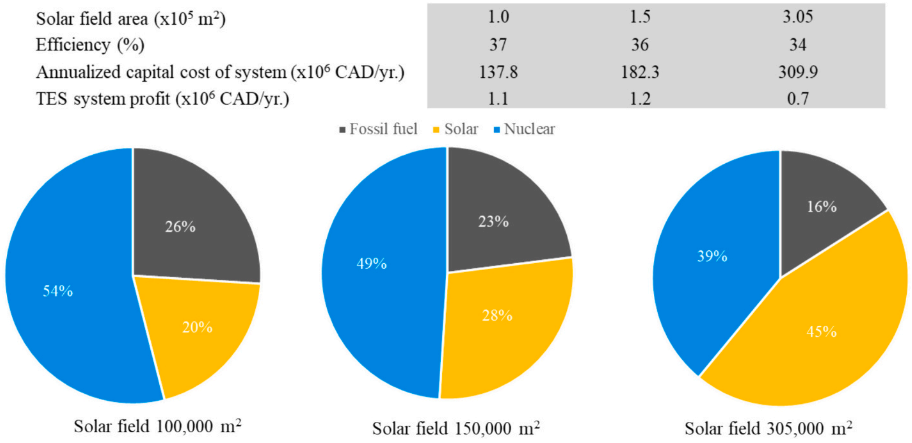
There are several types of thermal energy storage systems that are used to store and release heat energy. Some analyses are also conducted while considering generic TES to evaluate the thermal performance, safety factor and cost effectiveness. Likewise, Mann and Schneider [58] performed an economic analysis on the generic TES integrated with a NPP system for potential expansion in both demand and cost up to 2030. Their findings revealed that revenue experienced a 30 % increase. However, it was observed that the cost of the system was significantly impacted by the increase in size of the storage system, suggesting that there is still ample room for improvement in the implementation of TES.

2.4. Sensible heat storage

In this type of storage, heat is stored by increasing the temperature of a solid or liquid material. Sensible heat storage systems use materials with high heat capacity, such as water, rocks, or molten salts. The heat is then released by transferring it from the storage medium to another system, such as a heat exchanger. In order to examine the performance of nuclear/TES systems having sensible heat TES, Edwards et al. [59] performed the exergy analysis of 3 nuclear/TES systems with two different storage mediums for each system; LH-SMR with two-tank TES system (therminol and DowthermT as HTF), MHTGR with packed bed TES system (Alumina and solar salt as storage medium), and PB-FHR with two tank TES system (Alumina and solar salt as a storage medium). Liquid thermal storage indicates an exergetic efficiency of 92–93 %, while solid thermal storage exhibits an exergetic efficiency of 77–78 %. In the case of lower nuclear reactors, Therminol showed higher exergy efficiency and energy density. Conversely, for higher temperature nuclear reactors, solar salt demonstrated greater exergy efficiency, while alumina-packed bed exhibited higher energy density. The lower exergy efficiency observed in solid storage media can be attributed to the fact that energy stored is consumed by Alumina and salt to cover losses, such as auxiliary heating or pressure drop. However, it should be noted that these losses are primarily dependent upon the layout of the plant. In 1995, Sager et al. [46] conducted research on the development of a shield composed of SiC-SiC composite shells for use in a TES system. The primary objective of this shield was to reduce radiation damage resulting from fusion reactions. Additionally, this TES system was designed to serve the dual purpose of cooling the reactor, eliminating the need for an external cooling system.

Carlson et al. [60] proposed one stage sensible storage and two stage latent heat storage system for NPP and investigated various storage materials for these systems. In a two-stage system, the second stage is also categorized as sensible heating. Among the sensible storage materials considered, Therminol VP-1 exhibited the highest energy density, while concrete was found to be the most cost-effective option. A comparable pattern was observed in the context of materials utilized for the latent heat storage, wherein there existed a tradeoff between energy density and cost. However, the capacity factor of the plant equipped with TES experienced a 9.8 % increase in comparison to the base plant. Another study examined the outcomes of packed-bed TES under two distinct scenarios. The first case, referred to as the “wet storage case,” involved flooding the Hornfels rock bed with Therminol 66. In the second case, known as the “dry storage case,” the packed bed was allowed to reach equilibrium before being drained of oil. Dry storage was found to be more promising because it utilized crushed rock as a storage medium that significantly decreased the associated costs, as it was readily accessible and considerably more cost-effective compared to synthetic oil. Nevertheless, this methodology necessitated supplementary infrastructure such as piping, valving, storage facilities, pumping mechanisms, and instrumentation [61,62].

The optimization study on nuclear/TES was conducted by Kluba and Field [63]. The study focused on three cases, each corresponding to a different storage temperature range (55, 85, and 125 °C). Several optimization objectives were considered including the minimization of



Solar field area (x10^5 m^2)	1.0	1.5	3.05
Efficiency (%)	37	36	34
Annualized capital cost of system (x10^6 CAD/yr.)	137.8	182.3	309.9
TES system profit (x10^6 CAD/yr.)	1.1	1.2	0.7

Fig. 4. Economics analysis of different combinations of energy sources for hybrid nuclear/TES plant with solar, studied by Bayomy and Moore [56].

energy losses, the limitation of the impact of TES on the operation, structures, and components of the plant, and the maximization of the overall efficiency of the system. The highest temperature case was identified to be the most optimal due to its ability to achieve the highest round-trip efficiency while causing minimal disturbance to the existing plant and equipment. This was attributed to its efficient utilization of the heat transport and storage media. The benefit of this case was that it used the least amount of power when running in storage mode because the temperature range and enthalpy change were the largest, which consequently led to a reduction in steam export. Moreover, in the context of heat recovery, the energy was found to be effectively reintegrated into the system, resulting in a notable increase in the Rankine cycle efficiency of the additional power generation.

Carlson and Davidson [64] provided parametric research on the thermodynamic performance and cost of integration of TES with NPP covering practical charge/discharge durations, peak demand, and round-trip storage efficiency. This research examined conceptual designs for sensible and latent heat storage modules in order to determine the most efficient options and optimal operating conditions. The three configurations used in this study can be differentiated based on their charge and discharge operations. In Configuration I, the storage system was charged by utilizing a high-pressure steam supply, while steam was discharged to the low-pressure turbine. In Configuration II, the charging process involved the utilization of high-pressure steam, while the discharging process involved the release of preheated condensate into the steam generator. Configuration III utilized low-pressure steam for the purpose of charging, while it released steam to an additional Rankine cycle. The energy production ratio of Configuration III was found to be the highest (0.99) and it did not necessitate modifications to the primary cycle turbines or adversely affect the efficiency of baseload operation. Configurations I and III were found to have the capability to generate peak powers that exceeded 1.5 times the capacity of the baseload plant. Configuration II on the other hand was constrained by a peak power capacity that was a mere 1.1 times that of baseload. However, it was considered cost-effective within the tested range, despite having a lower energy production ratio compared to configuration III. The economic viability of sensible heat storage in a rock bed was found to surpass that of the latent heat storage, primarily because of the comparatively expensive nature of eutectic salt mixtures possessing suitable melt temperatures.

Mikkelson and Frick [65] presented a novel turbomachinery model design to integrate the concreted TES system in NPP to achieve seamless usage of stored energy. This model employed conventional conservation-law-based analysis via fluid network analysis. They tested their model using a real-time demand profile of 5 days. The model was also validated with the previous integrated energy storage models, and it was found that 20 % more power can be generated using the integration of a concrete TES system. This control system was augmented against the standard operating mechanism in order to allow the turbine to be operated flexibly between electrical demands of 70–120 % of nominal power.

Sensible heat storage technology is not limited to increasing the temperature of the storage medium to exact energy when needed. Certain concepts have demonstrated the efficacy of reducing storage temperatures for subsequent utilization in plant cooling or alternative storage purposes [66]. In a study, Li et al. [67] designed and implemented a nuclear/TES plant that incorporates a cryogenic energy storage (CES) system that involved the storage of liquid air/nitrogen. During peak hours, the liquid air stored in a tank was initially pressurized by means of a Cryogenic pump. The cold energy from the high-pressure air was transferred to the cold storage media, which was then pre-heated by the stream of exhaust gases. Meanwhile, the secondary coolant within the NPP was introduced to further elevate the temperature and pressure of the air, which drove the turbine, thereby generating electricity. By effectively harnessing the thermal energy of NPP, CES technology may generate about three times the plant's rated electrical output during peak demand. Moreover, CES exhibited a round trip efficiency exceeding 70 % as a result of the increased topping temperature during the superheating phase, which also contributed to a significant enhancement in the thermal efficiency. The observed trend in round trip efficiency indicated that an increase in storage pressure results in a proportional increase in round trip efficiency, with a rate of approximately 0.8 % per unit increase in pressure.

Frick et al. [68] analyzed the small modular reactor (SMR) with two energy storage technologies (sensible heat storage and stratified chilled-water storage system). During periods of low demand, steam was redirected to a sensible heat storage system after being charged for a duration of 8 h, which corresponded to the maximum capacity of that system. Then, any excess steam was subsequently utilized for the generation of chilled water. They discovered that the implementation of this particular system effectively decreased the dryout of the steam generator by 15 % of the tube length during peak periods, resulting in a reduction to only 2 %. They reported that the steam generator could be protected from the negative impacts of repeated cycling in this specific region, but that could lead to stress accumulation and ultimately reduce of operational lifespan of the steam generator tubes.

2.5. *Latent heat storage*

Latent heat storage systems utilize the phase change of a material to store and release energy. During charging, the material absorbs heat and changes its phase from solid to liquid or liquid to gas, storing the energy as the latent heat. When the energy is needed, the material undergoes a reverse phase change, releasing the stored heat. For example, Aminov [69] developed the multifunction system by integrating latent heat TES with NPP in order to improve efficiency and safety, and assess the cost of modification. The suggested approach involved integrating a two-loop NPP with a multifunctional TES system that utilized the latent heat. During the discharging of latent heat TES, feedwater heating was employed to raise the temperature above the nominal level, thereby increasing the live steam flowrate without altering the power output of the reactor plant which resulted in high thermodynamic efficiency. When the TES system lacked steam-generation then the additional turbine in a NPP unit could produce an electric power output of 140 MW by elevating the temperature of the feedwater from 215 to 260 °C. The second approach considered was less complex and cost-effective. In the event of a power supply disconnection, TES would use core decay heat to generate steam and assist shutdown reactor thereby boosting safety. Furthermore, the economic efficiency of the proposed system demonstrated a positive annual net present value from this implementation. Another study by Aminov et al. [70] that conducted a numerical analysis on the use of latent TES to enhance heat transfer in a single column TES system. Fins were employed to optimize the heat transfer between PCM and HTF through an annular design for the purpose of discharging. It was discovered that the addition of fins enables the PCM to cool down uniformly.

Alameri et al. [71] proposed the prismatic-core advanced high temperature reactor (AHTR) with molten salt cooling system integrated with PCM based TES system (Fig. 5). A numerical approach was employed to predict the heat transfer coefficient of the proposed reactor and TES system, as well as to determine the flow development within the loops of the nuclear/TES system. Their analysis revealed that both the primary and secondary loops exhibit a laminar regime. Furthermore, the study also conducted an estimation of the neutronic parameters of the proposed reactor such as operating cycle, fuel loadings, temperature feedback coefficients, burnup rates, excess reactivities, peaking factors, and control worth. TES system comprised of 300 blocks based on PCM, with each block containing 1135 tubes filled with LiCl-PCM. It was assumed that the Nusselt number remained constant at a value of 4.363, which resulted in an under-prediction of the heat transfer coefficient.

A numerical approach was adopted to examine the performance of latent heat TES by Ali et al. [72], which utilized the triple-tube geometry

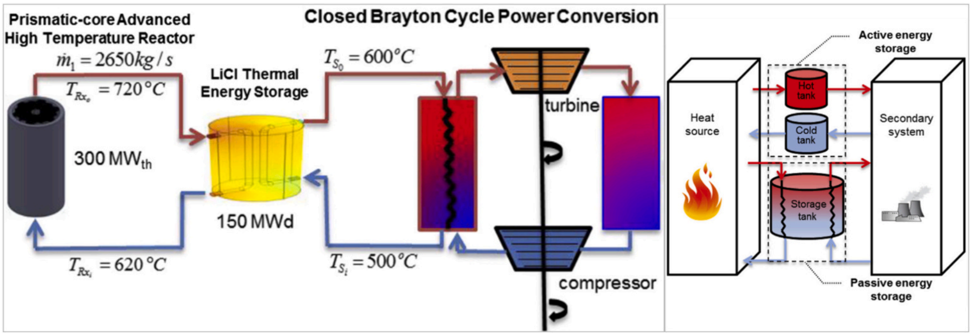


Fig. 5. Graphical representation of nuclear/TES proposed by Alameri et al. [71] (adapted with permission from reference [71], copyright 2019 Elsevier B.V.).

for TES with LiCl as phase change material and two different HTFs (FLiBe and helium). This numerical study revealed that the energy stored, was dependent on the fraction of liquid volume in accordance with the demand of the grid and that the variable load cycle stored more energy than the steady load cycle. Additionally, the findings indicated that a reduction in the mass flow rate led to a corresponding increase in the amount of stored energy. At lower mass flow rates, the helium extracted reduced amounts of heat, resulting in a greater degree of melting. Nevertheless, as the mass flow rate of helium increased, a greater amount of heat was extracted, resulting in the solidification of the PCM in order to release heat. The aforementioned research [73] also collaborated on enhancing the design of the TES (vertical triplex tub) to optimize its charging capacity and dynamic response to the electricity demand. The proposed design of the TES system consisted of two fluid loops. This design aimed to improve the efficiency of the charging and discharging processes by ensuring a uniform phase change process within the TES tubes. Additionally, this design allowed for the accommodation of sudden variations in electricity demands. Another investigation [74] conducted by this research group showed the evaluation of overall system efficiency via energy and exergy balances at various components in two different designs of the power generation process: Rankine and Brayton (supercritical carbon dioxide) cycles. Their findings demonstrated that about half of the exergy is dissipated during the operational phase of the reactor core. However, the losses incurred in the TES exhibited a notably lowered magnitude, observing <10 %, in comparison to the losses experienced in the reactor core. The advanced Brayton cycle was found to exhibit higher efficiency compared to the Rankine cycle. By employing efficient components, it was possible to achieve an overall efficiency system up to 50 %.

Soto et al. [75] performed the techno-economic analysis on two-tank molten salt TES integrated with a LFR nuclear reactor. The analysis was conducted over a whole year to examine the demand of summer and winter seasons, as well as the correlation between the requirement of charging capacity of TES (TES size) with the seasonal variations. The higher storage capacity exhibited commendable performance by effectively accommodating greater fluctuations, however, the cost of electricity increased exponentially above storage of 7 h. Furthermore, different market price scenarios were also discussed, and they found that the integrated system outperformed the base plant even if energy prices increased by a factor of two or more.

Ghazaie et al. [76] proposed a nuclear/TES plant as a potential solution for diverse co-generation scenarios involving district heating and electricity generation. It was observed that a high temperature was not necessary for the district heating system, even low-potential steam from low-pressure turbine stages were able to supply the necessary heat in the months of May, June, July, August, and September. The power loss factor resulting from steam extraction exhibited a variation from 11.1 % during the summer season to 24.5 % during the winter season. The cogeneration plant experienced a decrease in its net electrical output of approximately 1.5 % and 25 % during the summer and winter seasons, respectively. This reduction was attributed to the extraction of heat from the NPP, with rates of 19.1 and 129.9 MWth during the summer and winter seasons, respectively.

Kindi et al. [77] proposed an upgraded layout of a convectional NPP with PCM-based TES system and secondary steam generator plant. Fig. 6, depicts two TES systems (TES-1 and TES-20, both consisting of PCM tanks (PCM-1 and PCM-2) connected in series. The PCM-1 tank was charged by utilizing steam at elevated temperatures coming from the steam generator, whereas the PCM-2 tank was charged by utilizing steam derived from the PCM-1 tank. Nevertheless, TES-2 tanks were supplied with a lower temperature steam charge, which was obtained subsequent to the HPT and prior to the reheater. The reason behind using such configuration was that two systems could be incorporated by different proportion of solar and wind generation according to the geological conditions and seasonal demand variations. The economic analysis was also conducted by annualized cost savings of the system under various scenarios. This proposed plant had the potential to generate an additional 32 % of electricity, amounting to 2160 MWe, in comparison to its rated capacity of 1610 MWe.

Another approach to deal with excess energy, Ice thermal storage (ITS) systems, was proposed by Zhao et al. [66], as a potential solution to address the cooling water requirements and thermal efficiency of power plants during periods of high temperatures. The ITS provided a cost-effective strategy of utilizing low-cost off-peak electricity to produce ice, which afterwards could be used for supplementary cooling purposes during periods of high demand. The ITS offers a method for transferring an extensive quantity of electrical power from low-demand periods to high-demand periods. The incorporation of ITS in once-through cooling facilities situated in limited water source can yield considerable cost reductions and prevent essential power reduction and stopping of operations during periods of excessive heat.

Gong and Ottermo [78] conducted an optimization study on the output of a combined-heat-and-power cycle, with the aim of maximizing the capacity factor and cost-effectiveness of a nuclear/TES plant for district heating and electricity generation. The energy and exergy analysis conducted evaluated two different scenarios for heat and power generation. The first scenario involved both renewable and nuclear power sources, while the second scenario was based entirely on 100 % renewable sources. Their findings indicated that optimal values were achieved when a significant proportion of renewable sources was utilized. Furthermore, the exergy analysis results demonstrated that there was no substantial difference between the two scenarios. Moreover, the exergy destruction was primarily caused by the boiler, molten salt storage, and steam generator.

Prieto et al. [79] conducted a comparative examination of several heat transfer fluids used for TES using a techno-economic method that relied on their thermophysical properties. This work employed the correlation of thermophysical properties for FLiNaK, KCl-MgCl$_2$, LiCl-KCl, (LiNaK)$_2$CO$_3$, NaF-ZrF$_4$, and KF-ZrF$_4$, within the temperature range of 500 to 900 °C for their performance comparison. The study on economics reveals that the most economical choice is KCl-MgCl$_2$ mostly because of the comparatively affordable price of the salt. The material

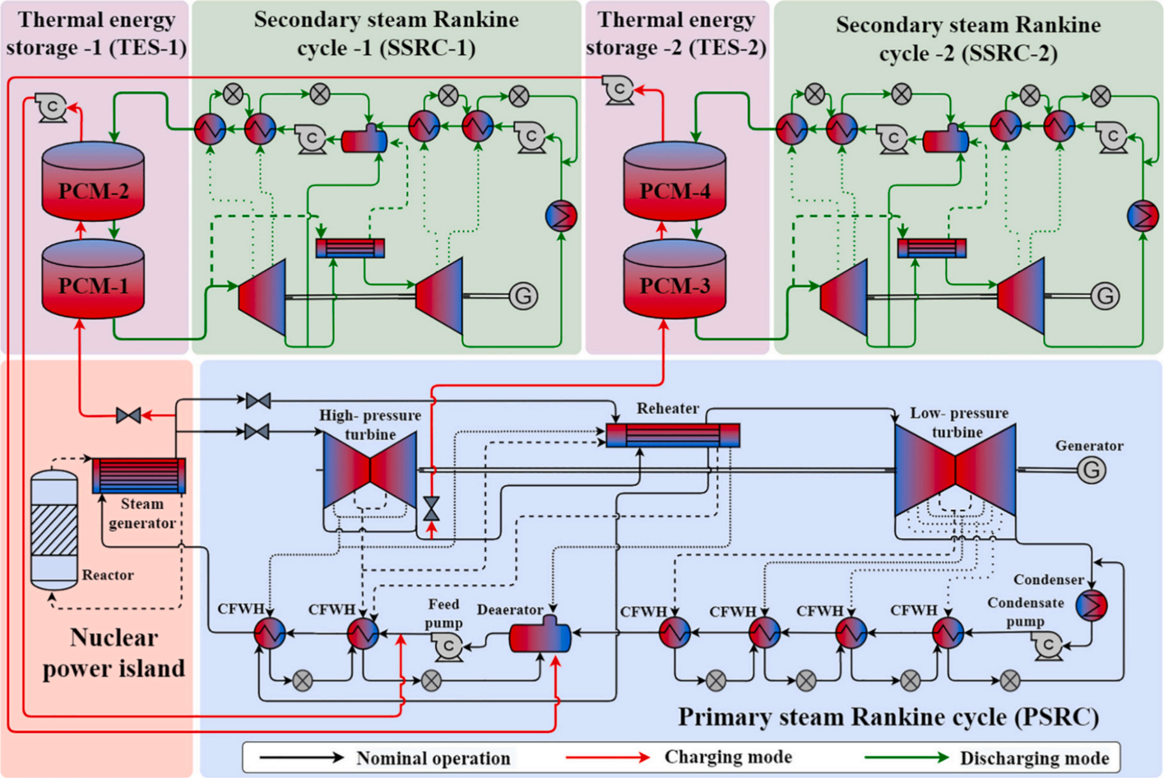


Fig. 6. Upgraded layout of convectional NPP integrated with TES and secondary steam Rankine cycle [77] (adapted with permission from reference [77], copyright 2022 Elsevier B.V.).

$(LiNaK)_2CO_3$ is the second most affordable choice overall, which further strengthens its suitability as a storage material for TES applications.

2.6. *Thermochemical*

The utilization of sensible or latent heat storage methodologies are capable of storing significant amounts of energy. However, these techniques pose a challenge in terms of long-term storage, particularly when responding to seasonal fluctuations. The primary concern pertains to the dissipation of heat resulting from improper thermal insulation. Hence, TES utilizing thermochemical reactions has been suggested as an appealing option for extended-term storage. During the charging process, an endothermic reaction causes the separation of compounds, which are subsequently stored in separate locations. During the process of discharge, the chemical reaction of the separated compounds results in the generation of heat. The system developed by Yurin and Egorov [80] involved the storage of excess energy during periods of low demand by means of electrolysis of water to generate hydrogen and oxygen, as well as the accumulation of hot water in a storage tank. It was ensured that when the station was de-energized, a low-power steam turbine would use the remaining heat from the reactor to produce power for the NPP's own use. One of the advantages of the hydrogen power system is its ability to conserve additional hydraulic reservoirs in the event of an emergency. In the context of hot water storage, it can be observed that there exists a proportional relation between the temperature of the hot water and the overall efficiency. An economic analysis was also conducted, revealing that the combined plant exhibited a payback period ranging from 15 to 19 years, with varied electricity rates between 0.64 and 0.83 ₽/kW because of predicted dynamics of the tariff [81].

2.7. *Other types*

Certainly, in addition to the broad categories mentioned earlier (sensible heat, latent heat and thermochemical storage) there are specific thermal energy storage systems according to their configurations [82]. Here are some examples.

Two-tanks: The objective of TES is to retain the stored heat without dropping the temperature. Because a drop in temperature is directly responsible for efficiency decrease when thermal energy is converted into mechanical and/or electrical energy. The two tanks are the most effective TES in ideal conditions without temperature reduction. The two tanks contain fluids at different temperatures, one at high temperature (hot tank) and the other at lower temperature (cold tank). During the charging cycle, the cold fluid is heated through the respective source depending upon the integration technology (solar-, nuclear-thermal, etc.) and stored in the hot tank. On the other hand, during the discharge cycle, energy is extracted from the hot fluid using a heat exchanger and the resulting fluid which is at a lower temperature is then stored in the cold tank. Energy storage efficiency can be increased to >95 % with proper insulation which indicates that the temperature of the thermal energy is not reduced. Most of the TES that are currently functioning are of two tank configurations [83]. References [84–86] can be consulted for a more thorough analysis of two-tank TES; however, the majority of the literature on two-tank TES is limited to solar applications.

Thermocline: While two-tank TES is the most efficient method of energy storage, it is also the most expensive because one tank is predominantly empty. Thermocline TES presents a viable solution for this issue. Thermocline TES involves the introduction and removal of hot fluid through the upper portion of the system, while cold fluid is introduced and removed through the lower portion. This arrangement results in the stratification of the hot and cold sections via temperature gradients and buoyancy effects. Nonetheless, the movement of the fluid induces a flow perturbation that has the potential to compromise the thermal stratification. This system necessitates a movement control mechanism for the insulation baffle, which is considered inconvenient. Due to this factor, the implementation of thermocline TES has not been widely utilized on a large scale for TES purposes [87]. More detail on thermocline TES may be found in References [88–91], although much of the literature on thermocline TES is only available for solar applications.

Packed bed: If the heat transfer fluid (HTF) is excessively costly or its energy storage capacity is insufficient, employing it as a heat storage medium may not be appropriate. Furthermore, it must be noted that if the HTF necessitates a significant amount of pressure to sustain its liquid form, a storage tank of considerable size will thus encounter substantial mechanical strain, thereby augmenting the overall expense of the TES system. Packed bed TES presents a notable benefit in terms of storing a considerable amount of thermal energy within a limited volume. This is attributed to the high thermal energy storage capacity of the heat storage medium. Nonetheless, it is important to note that there will always be a certain level of heat transfer occurring between the HTF and the heat storage medium, thus limiting the energy storage efficiency to <100 %. Consequently, the temperature of the discharged HTF diminishes over a specific duration. Stones and gravels are utilized as a sensible medium for storing heat due to their advantageous attributes of high thermal storage capacity and low cost. Due to the fact that latent heat possesses more intensity than sensible heat, PCM has the capability to accumulate significant amounts of energy within a considerably smaller volume. Nevertheless, the majority of PCMs exhibit a low thermal conductivity, hence resulting in slow charging and discharging rates [92]. Additional literature pertaining to the advancement of packed-bed thermal energy storage (TES) can be examined by reviewing the reference provided [89,93,94].

Steam accumulators: Steam accumulators (Fig. 7) are utilized for TES in several sectors in addition to the field of nuclear power. The extensive utilization of this technology can be attributed to their notable energy storage capabilities and remarkable ramp/response time. In a conventional system, steam accumulators are employed to store a mixture of water and steam during the charging cycle of a container, thus increasing the pressure of the steam at the upper section of that container. The mixture reaches equilibrium under saturation conditions and maintains this state throughout the charging process. During the process of discharge, the steam is released from the container through a release valve. As the discharging cycle continues, pressure and saturation temperature drop, flashing more liquid to steam [95].

There exist several alternative techniques for utilizing excess energy during off-peak periods. One such approach, as proposed by Nguyen et al. [45], involves the integration of additional cooling mechanisms (low-temperature organic Rankine cycle waste heat recovery). The proposed cooling system exhibited the ability to mitigate water consumption and associated adverse environmental effects. Approximately 10 % of the steam was utilized in the production of ice (or chilled slurry water) that was later used for the purposes of cooling and/or condensation. This plant exhibited optimal performance in regions where electricity rates were comparatively lower and ice storage was not a significant concern.

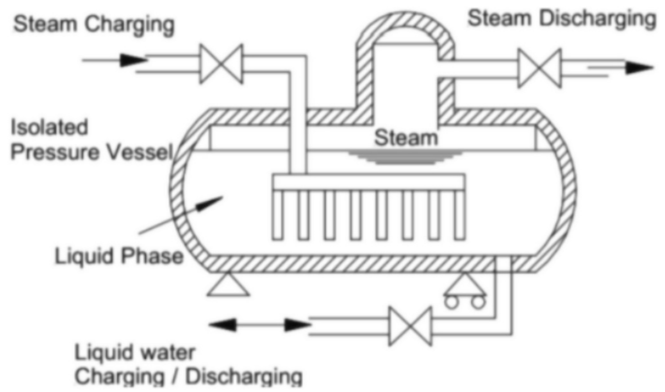


Fig. 7. Steam accumulator (adapted with permission from reference [97], copyright 2006 Elsevier B.V.).

Saeed et al. [96] investigated different TES technologies for NPP, including technology readiness level, size, temperature compatibility, ramp time, energy density, and environmental impacts. This investigation assessed the suitability of different TES systems for integration with advanced NPPs. It also gathered data on the maturity of these systems, and their pertinent performance characteristics, identifying areas of further research. This information is crucial for the continued improvement and development of these technologies. Among the technologies mentioned, solid-media storage and latent heat storage were determined to be the most suitable options for all temperature ranges. However, the utilization of a two-tank molten salt system demonstrates superior performance, though limited to low- and medium-temperature NPPs. Fig. 8 depicts the TES technologies employed for integration with different NPP.

3. ESS integration approaches/types of integration

The identification of the convergence points between ESS and NPP, or renewable/NPP, is of crucial significance as it has a substantial impact on the overall operational efficiency of the plant as including an additional component would result in increased energy losses. When making an assessment of where to redirect the flow to the ESS within the steam cycle, various factors are taken into account. Two conditions must be fulfilled for a successful diversion at the branch point. First, when mass flow rate is sufficient the placement of the branch point must be prior to the low-pressure turbine. Second, when mass flow rate is limited, it can be inferred that the optimal location for a branch point is after the low-pressure turbine. This is due to the fact that there are no apparent variations in the output of the steam cycle. The integration point, at which the branch flow of ESS is reintroduced into the steam cycle, is based upon the specific category of the ESS. In the case that the branch flow delivers thermal energy to the ESS, the magnitude of heat loss would exceed that of the pressure loss. Conversely, if the energy is transmitted in the form of work, the pressure loss cannot be considered insignificant.

Lee et al., [98] analyzed the different integration points of TES, highlighted with yellow backdrop, as illustrated in Fig. 9. In view of above discussions, sufficient mass flow rate conditions for this plant (Fig. 9), the location numbers 1, 3, and 6 were considered to be suitable candidates for the branch point. The first point is located close to the reactor, which may introduce safety concerns and was thus ignored. Based on its ability to provide a higher amount of energy to the ESS, location 6 was determined to be a better choice than the location 3, positioned prior to the inlet of the low-pressure turbine. Additionally, two more integration points were examined: 1) the integration point linking feedwater heater (FWH) #4 to the high-pressure turbine, and 2) the integration point connecting FWH #1 to the low-pressure turbine and the condenser. When the branch flow combines with FWH #4, the

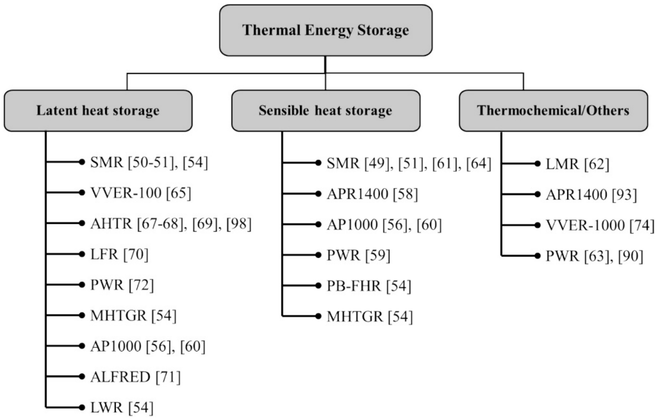


Fig. 8. Brief detail about NPPs that were examined using various types of TES.

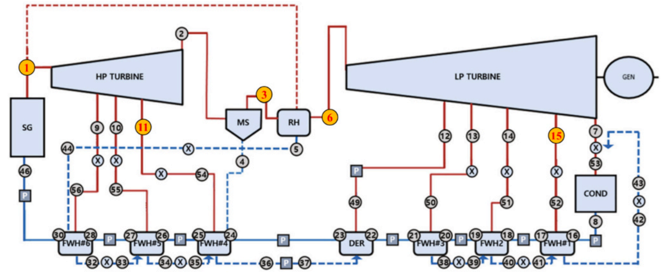


Fig. 9. Schematic of layout represents different integration points of TES in NPP, reported by Lee et al. [98] (adapted with permission from reference [98], copyright 2020 Elsevier B.V.).

ESS outlet pressure and temperature are assumed to be the same as the moisture separator outlet (location 4). When the point of integration occurs at the condenser, the outlet state of the ESS is equivalent to the inlet state of the condenser (location 7). It is important to note here that when the branch flow was 25 %, overall output of cycle was decreased by 44,17 % and 49.95 % for case of FWH # 4 and 1, respectively. Amuda and Field [62] conducted a study to evaluate the performance of various integration locations for TES systems for NPPs. These integration locations included 1) between the mechanical separator and low-pressure turbine, 2) with FWHs of the high-pressure turbine, and 3) after the condenser. These configurations successfully achieved comparable levels of temperature, pressure, charging time, and capacity. However, it is worth noting that a larger size of the TES system is required for the first configuration which is considered as a drawback.

In NPPs, the reactor coolant serves as an intermediate layer for containing radioactivity. As a safety precaution, the coolant is typically not allowed to exit the containment structure. This safety concept, as well as the high-volume requirements for TES systems, imply TES integration into NPPs through heat exchange between reactor coolant and secondary HTF. Therefore, in order to achieve nuclear safety standards, it is possible to place the heat exchanger responsible for transferring heat between the reactor coolant and HTF within the boundaries of the reactor containment structure. Subsequently, the high-temperature HTF is transferred from the reactor containment structure to an external location for the purpose of storing energy in a TES system. However, the second explanation for the importance of this heat exchange procedure arises from the compatibility concerns between various TES systems and their corresponding HTF requirements. The layout of the reactor containment structure in existing NPPs typically lacks the necessary flexibility to accommodate the installation of large-scale heat exchange equipment.

The preceding discussion has addressed diverse concerns pertaining to the integration of TES with NPP. However, the primary focus of the industry remains centered on the financial aspect. The study conducted by Borowiec et al. [99] examined various integration scenarios of TES having a focus on cost implications. The analysis was carried out while considering a maximum of 40 % contribution from renewable sources, specifically 10–30 % from wind and 10–30 % from solar, in the overall power generation process. Additionally, this examination was also conducted for various electricity markets within the United States. The optimal cost-effectiveness of TES is achieved with a smaller size of up to 5 h, however, the larger thermal efficiency of the plant requires a larger TES size. In some markets, it is also observed that optimal performance can be achieved with larger TES sizes. Brief summary of literature on nuclear-TES which is discussed in the current review is tabulated in Table 1. A flowchart is also added (see Fig. 9) to show various TES technologies integrated with nuclear power plants. It can be observed that the trend is the integration of latent storage with various types of nuclear power plants.

3.1. *Challenges related to the integration of NPP with TES*

An innovative reactor coolant that serves the dual purpose of transferring heat to the turbines and functioning as a storage medium is the need of the hour. However, it is worth noting that only a limited number of thermal storage media possess the necessary technical compatibility for this task. It is probable that a heat exchanger would be utilized to facilitate the transfer of heat from the reactor to the storage medium. Both of these alternatives are likely to result in raising the expenses associated with the development and operation of the reactor system, leading to a substantial focus on the design of materials and heat exchangers [100].

Several reactor alternatives can be integrated into a combined nuclear/TES system, which include but are not limited to, light water reactors, very-high-temperature reactor, advanced high-temperature reactor, sodium-cooled fast reactor, and lead-cooled fast reactor. Although high-temperature reactors (HTRs) offer greater potential efficiencies due to their higher operating temperatures, it is noteworthy that there is no technical limitation that precludes a light water reactor (LWR) from functioning as the heat source in a nuclear/TES system. The possibility for enhanced system performance related to HTRs is counterbalanced by the considerable challenges posed by materials compatibility, reactor safety, and licensing requirements that must be addressed prior to the commercialization of a conceptual design. The potential efficiencies of LWRs may be constrained by their capacity to achieve lower temperatures. However, the challenges associated with material compatibility, reactor safety, and licensing have been comprehensively realized, particularly in terms of the reactor's operation.

Currently, all the power reactors in the United States are LWRs, with a combination of PWRs and BWRs. As previously stated, PWRs are the only viable option for utilization with TES due to their existing design that incorporates an intermediate heat exchanger. This design choice eliminates the need for phase change, which adds unnecessary complexity to the heat source with minimal benefits [101]. Design, safety, and regulatory issues are the three key areas where linking large TES to a nuclear power station presents difficulties. Design challenges refer to the modifications required in the reactor design to connect a substantial thermal power unit to the primary coolant unit of a nuclear power facility. The safety challenges associated with large-scale TES pertain to comprehending the potential impact of TES on the safety foundation of NPP, as well as its influence on the progression of accidents at the plant. The incorporation of TES into a novel NPP introduces uncertainties to the regulatory process, thereby posing regulatory challenges [102]. The integration of TES into NPP present significant design challenges, primarily related to the coupling of a substantial thermal mass to the reactor coolant system and the material compatibility issues arising from the thermal storage materials. A few TES techniques may exhibit a high degree of coupling with the reactor and coolant, whereas others may demonstrate a lower degree of coupling. The implementation of a thermal block, composed of a material identical or nearly identical to the primary coolant of the reactor and directly connected to the reactor core, may have a direct influence on the thermal feedback and kinetics of the reactor. The comprehensive identification of important design challenges necessitates the development and evaluation of a conceptual integrated nuclear/TES system, which is an area of prospective investigation [103].

4. Future prospective and trends

In recent years, several advancements have been made in the field of energy storage, offering new perspectives and trends for mechanical and thermal energy storage in nuclear power plants.

Table 1
Brief summary of literature related to nuclear/TES plants.

Type of NPP	Capacity of NPP	Types of TES	Storage materials	Operating Temp	Energy stored	TES integration point
Excess nuclear and thermal energy [27]	1.22–1.5 kWh	Compressed air storage system	Air with oil-based HTF	Different for different types (250–635 °C)		Waste heat goes to Energy storage system
NuScale SMR plant (PWR) [53]	Hybrid power 80.354 MW	Sensible heat storage (2-tank), compressed air and pumped hydro	2-Tank with molten salts (60 % NaNO$_3$) and (40 % (KNO$_3$)	255 and 580 °C	12 h storage, above 59 % round trip electricity efficiency	Combining steam loop of solar PV & nuclear steam generator
SMRs [54]	125 MWthNPP and CSP 100–150 MWe	Packed-bed TES	Solar salt	Molten salt 500–570 °C	15 h storage (app. 50 Mwe)	Combining steam loop of CSP and nuclear steam generator
SMRs [55]	105 MW	Grid-scale ternary-Pumped TES	Therminol VP-1 for hot tank	423 °C	3407×10^6 kJ	Between conversion loop
SMR and concentrated solar tower [56]	160 MWth	Sensible and latent	Therminol, dowtherm, solar salt, hitec salt and hitec XL salt	255–545 °C	Charging and round-trip storage efficiency of 237,268 MWh/year and 96 %	After reactor and turbine
APR1400 [98]	3983 MW	Mechanical ESS		778–788 °C	25 % branch flow rate	Different merging point (section 3)
SMR [65]	160 MWth	Concrete TES	HTF (sensible)	RFT = 498.05 °C	Flexibility 70–120 %,	After turbine
VVER-1000 [69]	1000 MW	Latent TES with additional turbine	59 % NaOH + 41 %, 40 %85 Ca (NO3)2 + 59.15 % LiCl and 65.5 % LiOH + 34.5 % LiCl	215–260 °C	Additional turbine can produce 12 MW	Before turbine, after steam generator
VVER-1200 [70]	1200 MW	Single column latent TES	LiNO$_3$ and 18.5 % NaNO$_3$ + 81.5 % NaOH	200–300 °C	Additional turbine can produce 12 MW	Between HPT and LPT
AHTR [72]	300 MW	Latent heat storage system	FLiBe, LiCl		150MWd	After reactor
LFR [75]	950 MWt	Two tank molten salt (latent heat)	60 % NaNO and KNO3)	Up to 570 °C, 560 for molten salt	39 % of total energy flow used to charge the TES	Two-tank configuration before high pressure turbine
PWR [45]	2.2 GW	Cool TES (vacuum ice maker)	Ice/water slurry	4.4C for TES HTF	Off peak energy storage capacity of MCT cooling 1968 MWh/day	After turbine and coupled with ORH-WHR
LW-SMR, MHTGR and PB-FHR [59]	600 MWth, 236 MWth	Two tank and packed bed configuration	Molten salt (40%KNO3 and 60 % NaNO3) and HTF (therminol66 and dowthermT) and Alumina (Rocks)	Steam 280 °C, helium 1000C, core outlet pebble 700		After reactor
(CHP plant capacity) [78]	123 MW	Two-tank molten salt storage	Solar salt	150–600 °C	–	Wind power to HTS
LWR [66]	1520 MWe	Ice thermal storage	Ice	−5–20 °C	1-Gwe	Separate ice production unit
PWR [67]	250 MW	Cryogenic energy storage	Cryogen (liquid air)	Max 560 °C	76.75 MW	Separate loop
AP1000 [60]	1100MWe	Two types; 1) one stage for sensible and 2) two stages for latent	Sensible heat storage (concrete, silica and therminol VP-1) and latent heat storage (NaNO3: NaOH(41:59 %), NaNO2, LiCl: LiOH (37:63), Bismuth)	271 °C	Power and efficiency increase from 690 MW and 0.835 to 829 MW and 0.840	Between steam generator and HPT
APR1400 [62]	4011.5 MWt	Sensible heat storage system	Therminol 66 for wet storage and dry storage for packed bed hornfels rock	323.9 °C	8 h charging (app. 19,200 MWt-h per day)	(i) between mechanical separator and LPT, (ii) with FWHs of HPT, and (iii) after condenser
AHTR [73]	300 MWth	Triplex-tube containers	FLiBe, LiCl	608.45 °C	Charging = 27 h and discharging = 17 h	After reactor, before heat exchanger of turbines
ALFRED [76]	300 MWth	Rotated square arrangement of tubes in cylinder (latent heat)	Erythritol	leadTemp = 327 °C, coreTemp = 480 °C	130 MWth	With HPT and LPT
PWR (APR1400) [63]	Licensed 3983 MWt	Sensible heat storage system	Therminol 66	3 operating temperature ranges 55 °C, 85 °C, and 125 °C	Round-trip efficiency 80 %	After reactor, before getting into HPT
Prismatic-core AHTR [74]	300 MWth	Phase change material (PCM) triplex-tube containers	LiCl	720 °C		Between reactor and steam generator
AP1000 [64]	1050MWe	Sensible and latent heat storage materials	Rock, NaNO3:NaOH (18.5:81.5), NaOH:NaNO2 (73:27) NaOH: KON (50:50)	231 °C	Charging and discharging duration are 2–10 h	3 configurations
VVER-1000 [80]	1000 MW with 292 working days	Electrolysis	Hydrogen		65 MW is supplied	Some steam was fed to electrolysis chamber
Prismatic-core AHTR [103]	300 MWth	LiCl thermal energy storage	LiCl	620–720 °C	150 MWd	After reactor, before Brayton cycle
SMR [68]	530 MWth	Two-tank sensible heat storage system and a	Therminol-66, -68 and -75	299 °C	8 h of charging	Bypass steam to TES

(*continued on next page*)

Table 1 (*continued*)

Type of NPP	Capacity of NPP	Types of TES	Storage materials	Operating Temp	Energy stored	TES integration point
		stratified chilled-water storage system				
European PWR [77]	4520 MWth	PCM-based TES	$NaNO_2$ (PCM-1), 53 % KNO_3 + 40 % $NaNO_2$ + 7 % $NaNO_3$ (PCM-2 and − 4), and 87 % $LiNO_3$ + 7 % NaCl (PCM-3)	208 °C	Charging phase is 64 %	2 TES with SG and HPT

- Advancements in storage and manufacturing materials should lead to the development of more efficient and durable energy storage systems.
- The integration of renewable energy sources with nuclear power plants should drive the need for flexible and scalable energy storage technologies.
- Smart grid technologies and advanced control systems have the potential to enable better integration and management of energy storage systems in nuclear power plants.
- The development of advanced computer modeling and simulation tools has the capability to aid in the design and optimization of energy storage systems for nuclear power plants.
- Numerous contemporary nuclear reactors are currently under development, with a particular emphasis on enhancing their compatibility with EES in order to increase flexibility.
- The economic aspects of such systems are of significant interest for ongoing research, as the electricity market exhibits variations worldwide due to geographical conditions and resource availability.
- Moreover, based on recent studies, there are several emerging trends in the field of TES integration such as the integration of TES technologies to achieve potentially higher operating temperatures, the adoption of a cascade concept involving modularized units, and the implementation of mechanical circulation mechanisms for granular particles.

5. Future recommendations

Although significant advancements have been made in the development of ESS for NPP to enhance efficiency and safety, there remain certain inconsistencies and challenges for further refinement. Most importantly, technical issues persist, requiring continued research and investigation in the field of nuclear/TES. The study aims to evaluate the TES system for NPP with the objective of identifying potential solutions for practicality such as;

1. During a grid failure, the operation of a TES system in a NPP is simplified to the extent that it can function as an independent backup power source individually. The focus shifts to managing the stored thermal energy efficiently, ensuring it is used to maintain operational stability and meet critical demands.
2. The safety of energy storage systems is designed to operate independently from nuclear reactors. This separation ensures that in the event of a failure in either system, the safety and operation of the other system is not compromised. Additionally, it is imperative to ensure that the systems are capable of separately and securely shutting down in the event of a cooling failure.
3. The system exhibits a high degree of resilience in effectively adjusting to real and reactive loads, while also possessing the ability to operate in a flexible manner. Furthermore, it demonstrates a notable resistance to potential harm caused by external factors, such as grid anomalies. The reactor remains unaffected by external grid events as it is effectively insulated from the grid through the utilization of heat storage mechanisms. Does not have an impact on the implications of other external events.
4. The capacity to function autonomously in island mode, wherein there is no reliance on external transmission load or electrical power supply. The reactor is connected to a heat storage system and operates consistently in island mode without relying on an external power source from the grid.
5. The electric market is undergoing rapid transformation due to the increasing demand for low-carbon power generation. Consequently, there is a growing need for cycle assessment, which is essential for quantifying carbon footprints. However, it is worth noting that this particular area of research remains relatively unexplored.

Further research and development efforts are necessary to optimize the design and operation of thermal EES specifically tailored for NPP. Innovations in materials, storage mediums, and heat transfer techniques can enhance the effectiveness and reliability of such systems, unlocking their full potential.

6. Conclusions

The implementation of green energy involves not only the research of novel energy sources but also the enhancement of existing power generation resources, resulting in reduced carbon emissions and increased power output; thus, this review article looks at how energy production from NPP's can be enhanced through the integration of ESSs (especially thermal energy storage systems).

TES systems have the potential to significantly improve the overall energy availability, safety, operational flexibility and cost effectiveness of nuclear power plants. During unexpected shutdowns, the instantly available thermal energy generated by a nuclear plant or steam generator can be stored in a TES system. Nuclear power facilities can improve load balancing and operational flexibility by using this stored energy during high demand. TES devices can act as heat sinks in emergency situations like coolant loss where the reactor can avoid overheating by gradually releasing thermal energy.

According to trends, energy storage systems capacity is supposed to be designed in the way to store surplus energy without compromising the instant demand before adding this stored energy into operation to meet the requirement of on-peak demand. This range varies from 50 to 150 MW with the charging time 5–8 h. In research, therminol and rocks are commonly suggested as sensible storage materials. As for latent storage materials, salts, particularly eutectic mixtures of salts, are being explored due to their effectiveness and affordability, as well as their ability to boost heat transfer compatibility. The primary focus of researches in the field of latent heat storage is on nitrates and chlorides salts. For operating conditions, high temperatures are considered favorable for latent heat storage; however, they present a control challenge. Most research has focused on two tank systems, which have been found to be efficient but more costly than thermoclines. A packed bed method is effective for storing sensible heat.

Regarding integration, the majority of studies have discovered that directly transferring heat from the steam generator to the TES system leads to a significant decrease in turbine performance. However, this trade-off is necessary in order to optimize the efficiency of both the plant turbines and the TES systems. The storage of this excess energy occurs during off-peak periods, making the reduced efficiency of turbines less relevant compared to the efficiency of TES systems. The efficiency of a TES system can be measured using two methods: round-trip efficiency, which accounts for losses throughout the charging and discharging process, and thermal efficiency, which considers losses in the system's components. Most studies have shown round-trip efficiencies ranging from 70 % to 85 %, while thermal efficiencies have been found to be over 90 %.

Despite the fact that there are still some technical challenges involved with the integration of TES with NPP, which is highly dependent on the type of nuclear reactors as discussed in Sections 3 and 5. Overall, the incorporation of TES with NPP offers numerous significant advantages, which provide sufficient justification for its implementation as previously described. Furthermore, the present review will serve as a valuable source for obtaining comprehensive insights into the deployment of nuclear/TES systems.

CRediT authorship contribution statement

Muhammad Faizan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Ahmed K. Alkaabi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Binjian Nie:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Imran Afgan:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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