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Abstract

Advanced nuclear power plants (NPPs) will potentially need to operate in environments where power generation flexibility is more highly valued than the stability or baseload generation capability for conventional demand curves. Thermal energy storage (TES) systems would enable NPPs to respond nimbly to market variability and could also position advanced NPPs to participate differently in restructured markets, thus further enhancing their economic competitiveness. TES systems could also benefit the electric grid by eliminating the need for peaking plants, as well as by improving the economic performance of baseload NPPs. While TES technologies afford a unique opportunity to address many of these challenges, the applicability of these systems is also complicated by the fact that various advanced NPPs are designed differently, each with its own temperature range, size, operating fluids, and operating conditions. Hence, TES systems face significant barriers to investment, as more information on their compatibility and performance metrics is needed to quantify the advantages provided by each, as well as the challenges these technologies might face if coupled with a particular type of advanced NPP. This study explores the possibility of integrating a wide variety of TES technologies with various categories of advanced NPPs, based on their operating characteristics. To help decision makers, users and developers decide which TES technology is best suited to a particular category of advanced NPPs, this research present a Phenomena Identification and Ranking Table (PIRT) analysis of 10 TES systems that could potentially be coupled with advanced NPPs, which themselves are divided into nine categories based on their operating conditions. Each advanced NPP category is evaluated for compatibility with the 10 TES systems by assembling and discussing a database of information concerning 10 engineering questions, defined herein in as figures of merit (FOMs), such as: technology readiness level (TRL), temperature compatibility, energy density, size, cycle frequency, ramp time, realignment frequency, geographic needs, environmental impact, and interventions. By assembling a database of information concerning the TES technologies' compatibility with various advanced NPP systems, this study can help developers acquaint themselves with a particular TES technology before choosing to build a new integrated installation.

Keywords: thermal energy storage, integrated energy systems, hybrid systems, advanced nuclear reactors, microreactors, small modular reactors.

1. INTRODUCTION

Distributed energy generation is becoming more and more common as new green energy sources (e.g., wind and solar) are added to the U.S. energy mix. As a result, other energy supply sources—specifically the current fleet of nuclear power plants (NPPs)—now operate in an environment in which flexible generation is more valued than baseload generation. As the energy supply and distribution continue to further evolve, thus causing an increased net demand variability on the grid, advanced NPPs will be expected to operate in a more competitive energy market than that faced by the current NPP fleet. For advanced NPPs to be competitive and economical in such an evolving grid, integrated energy storage techniques represent a unique way of increasing revenue and reducing costs by providing stable operating capabilities. But though integrated energy storage technologies will enhance the economic competitiveness of NPPs, it is a recognized challenge for utilities to quickly identify top technologies for integration with nuclear power given the large number of potential options.

The Department of Energy Office of Nuclear Energy supports research into integrated energy systems (IESs). A primary focus of the IES program is to investigate how nuclear energy can be used outside of traditional electricity generation [1]. The inclusion of energy storage has proven vital in allowing these systems to accommodate this shift to support multiple energy markets. Several energy storage technologies are well suited for performing many of the services desired by power companies and developers. In particular, thermal energy storage (TES) provides several advantages when integrated with nuclear energy. First, nuclear reactors are thermal generators, meaning that fewer energy transformation mechanisms are required when thermal energy is used as the coupling energy resource. Second, TES systems would preserve nuclear energy in its original form (heat), enabling much more flexible use when the stored energy is recovered (e.g., electricity production or steam supply for industrial systems). Third, a thermal buffer allows a decoupling between the nuclear core and the power conversion unit that historically has dictated system operation. In previous work, Idaho National Laboratory (INL) analyzed 10 TES technologies for coupling with light-water reactors (LWRs) [2]. In comparison, the work presented herein focuses primarily on TES systems that are well suited for coupling with advanced NPPs. Such findings support nuclear generation for dynamic operation in an evolving grid and energy system that look very different from when the current NPP fleet was first constructed.

One key objective is to determine the proper TES technologies for each type of advanced nuclear reactor system. This is accomplished via figure of merit (FOM) analysis to explore and rank a wide range of TES technologies, based on their compatibility with a specific set of operating conditions. Key factors considered in FOM analysis include technology readiness level (TRL), temperature compatibility, energy density, size, cycle frequency, ramp time, availability, realignment frequency, geographic needs, environmental impact, and minimum turndowns. The FOMs were used systematically as the basis for developing a Phenomena Identification and Ranking Table (PIRT), which is a process that has been applied to many nuclear technology issues, including nuclear analysis, to help guide research or develop regulatory and technical requirements. In the PIRT process, each FOM was assigned a different value, depending on the type of advanced NPP being studied. The operating temperature and power output of the NPPs were carefully considered in order to systematically determine the prime TES candidates for potential coupling. The PIRT analysis results could provide a database of information concerning the available TES technologies for grid stabilizations. The technologies herein are outlined and discussed in detail so that, as they are developed further, this PIRT analysis can be updated. Meanwhile, the framework set forth will remain foundational. In follow-up work, the results and findings from this study will be applied to evaluate the economics of the most promising method of thermal energy dispatch to end users.

2. BACKGROUND

2.1 Advanced Nuclear Power Plants

When compared to the current fleet of LWRs, advanced nuclear reactors are distinguished by one or more fundamental attributes, such as nuclear fuel type, reactor coolant, size, inherent safety, modularity, design simplicity, cost-competitive electrical power generation, and proliferation resistance (i.e.: it is much more difficult to divert materials from its the fuel cycle for nuclear weapon uses). One key attribute of many advanced reactors includes provision of high-quality heat (500–1000°C), which is of notable interest to IESs, as this high-temperature heat can be extracted to drive industrial processes or enhance efficiency. Numerous advanced nuclear reactors are currently being developed by private industry, often with support from federal research laboratories. Advanced nuclear reactors are primarily classified by coolant type as follows: 1. Liquid-metal fast reactors (LMFR) which includes Sodium-cooled fast reactors (SFR) and Lead-cooled fast reactors (LFR), 2. Water-cooled reactors which includes pressurized water reactors (PWR), boiling water reactors (BWR), and Heavy-water reactors (HWR), 3. Gas-cooled reactors (GCR) including Gas-cooled fast reactors (GCFR) and High-temperature gas-cooled reactors (HTGR), 4. Molten-salt reactors (MSR) including Molten salt cooled reactors and Molten salt fueled reactors.

In this study, advanced reactor systems were categorized based on their operating temperature range and thermal output. Three operating temperature ranges were used: (1) low (<350°C), corresponding to advanced light and heavy water reactors; (2) medium (350–650°C), corresponding to MSRs, SFRs, and LFRs; and (3) high (>650°C), corresponding to GCRs and HTGRs. Each category was then further divided up into three subcategories: (1) micro/small (<25 MWth), focusing on microreactors; (2) small to medium (25–750 MWth), focusing on small modular reactors (SMRs); and (3) large NPPs (>750 MWth). This classification forming the 3x3 matrix is shown in Table 1, with each category being evaluated based on 10 engineering questions, defined herein as the FOMs.

Table 1. Classification of advanced NPPs, based on their operating temperature ranges and thermal outputs, for PIRT analysis.

PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level									
[redacted]									
Energy Storage density (system size)									
[redacted]									
Ramp time (response time)					PIRT EVALUATION				
[redacted]									
Realignment frequency									
[redacted]									
Environmental concerns									
[redacted]									

2.2 Thermal Energy Storage Technologies

TES technologies accumulate and release energy by heating, cooling, melting, or solidifying a storage medium so that the stored energy can later be used for various applications (i.e., power generation) by simply reversing the process. When coupled with NPPs, TES technologies could store, in the form of heat, any excess energy not being used for power production. This energy could later be recovered to generate heat or electrical power during periods of high demand/pricing for grid electricity. This would enable NPPs to operate at maximum capacity, without having to load follow to match the demands of the market, thereby increasing their efficiency and reducing any mismatches between energy supply and demand.

While TES technologies can be classified in many ways, all classifications are generally based on three common avenues of energy storage: sensible heat, latent heat, and thermochemical energy. The TES technologies considered in this study are further classified and grouped based on a combination of factors, including heat storage method, storage medium, and the installation form-factor or geometry of the technology. With such classification in mind, the technologies analyzed in this study are discussed in the following sections.

2.2.1 *Liquid Based Sensible Heat Storage*

In sensible heat systems, energy is stored by raising or lowering the temperature of a storage material without changing its phase. Energy storage is driven by changes in the system's internal energy as the storage medium experiences a temperature change. Due to the myriad materials available for heat storage, sensible heat technologies operate over a wide range of temperatures. The factors that influence energy storage density are the mass of the storage material, its specific heat capacity, and the temperature change brought about in the system during its operational lifecycle.

At a system level, sensible heat storage technologies consist of a storage medium (liquid or solid), a container (usually a tank), and a heat transfer fluid. The heat transfer fluid absorbs the thermal energy from the heat source and transfers it to the storage medium. It can also do basically the same thing in reverse: namely, absorb heat from the storage medium and deposit it to a heat user. TES designs can involve one or more heat transfer fluids, depending on the nature of both the heat source and the power block consuming the heat. In some cases, the heat transport fluid can also be used as the storage medium itself. The following sections describe some commonly used liquid-based sensible heat storage system designs.

2.2.1.1 ***Two-Tank System***

The two-tank system is the most common form of sensible heat storage technology for high-temperature applications that require hours of storage capacity. This technology was deployed on a large scale in concentrated solar power (CSP) plants in which, depending on the operating temperature, the heat transfer fluid and the storage medium can be thermal oils or molten salts. In some applications for which both fluid types are used, the thermal oils usually operate as the heat transfer fluid—transferring heat from the generator to the storage system—and the molten salts serving as the heat storage medium. Operation of this TES technology involves the use of two large tanks, each capable of storing the entire mass of the storage medium; a heat source to charge the TES system; and a power block to discharge it. Figure 1 presents a schematic of two-tank TES systems coupled to two CSP plant configurations.

Within the two-tank TES designs, a further classification can be made based on whether the heat storage medium is heated directly by the heat source, or indirectly via a heat transfer fluid. During the charging cycle in the indirect setup, the storage medium is first pumped from the cold tank and through an intermediate heat exchanger that couples the system with the heat source, then transferred to the hot tank for storage. During the discharge cycle, the system operates in reverse: depositing its heat to a fluid that is then sent to the power block. The power block uses the heated fluid to produce steam that is then expanded in a turbine to generate electricity. The direct design differs from the indirect setup only during the charging cycle, since the storage medium is directly heated by the heat source prior to being transferred to the cold tank.

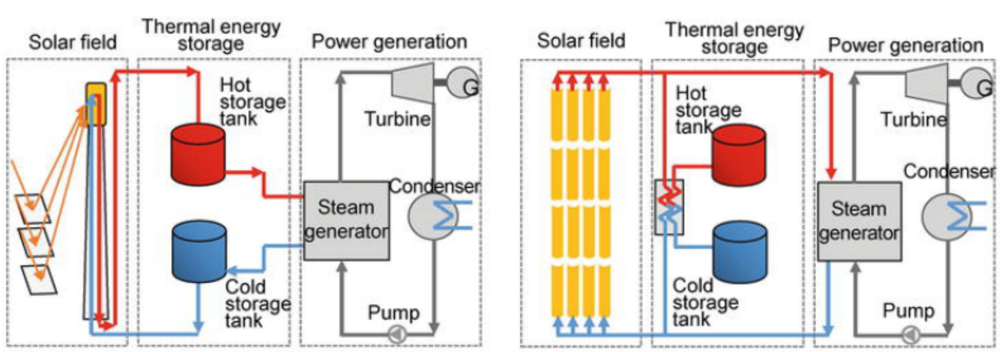

Figure 1. Schematics of two-tank TES systems connected to a solar-tower-based CSP system *[3]*.

Depending on its size, a two-tank TES system can generate anywhere from a few megawatts to hundreds of megawatts of power, as proven in CSP plants [4][5][6]. Also, this type of storage has been studied in detail for integration with nuclear power plants [7][8] Because this technology has been widely studied and deployed, it can be considered a prime candidate for potential coupling with NPPs. Figure 2 shows a schematic of the potential coupling between a nuclear reactor and a two-tank TES design.

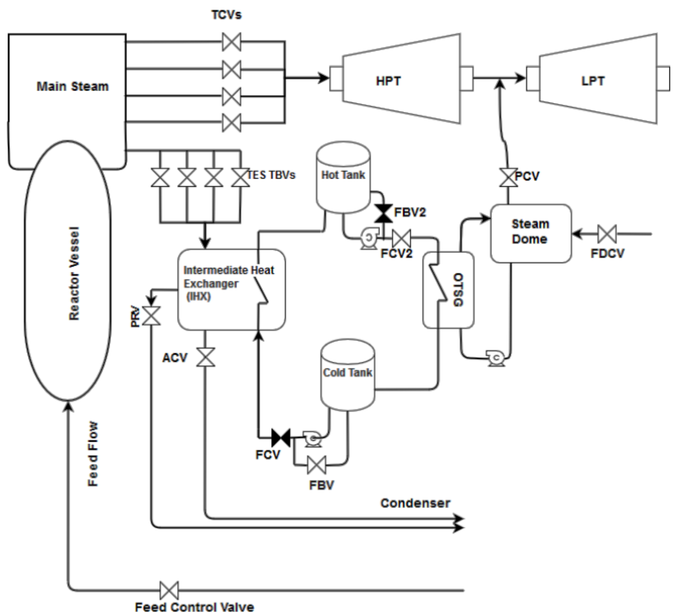

Figure 2. Schematic demonstrating coupling between a nuclear reactor and a two-tank TES system [9].

For reactors that operate at lower temperatures (~150–350°C), thermal oils such as synthetic heat transfer fluids (e.g., Dowtherm™ or Therminol®) can be used as heat transfer fluid to carry the sensible heat to an insulated TES vessel located outside the containment. Dowtherm™ is a mixture of alkyl benzenes, while Therminol® is a modified terphenyl [10][11]. Both working fluids have been used in solar systems and are commercially available. For temperatures above 400°C, molten salts are the only viable option for sensible heat storage using the two-tank setup. Molten salts are very well understood, and possess key features such as low vapor pressure, low costs, and reduced risk during accidents as they solidify when they leak. The properties of molten salts and thermal oils are discussed in greater detail in Section 4. In all cases, the heat transfer fluid used for two-tank systems must be stable at the reactor's operating temperature, remain liquid near the reactor coolant temperature at atmospheric pressure, and have a melting temperature that is below room temperature. The most obvious application of molten salt energy storage systems is variable supply resource integration since molten salts are most often used with concentrating solar power plants. Since molten salt energy storage systems are already being used with CSP plants, the discussion and results of this particular TES technology is also relevant to CSP power plants.

2.2.1.2 *Thermocline Systems*

Thermocline thermal storage technology is based on replacing the two-tank system with a single tank. Within the thermocline tank, the hottest fraction of the storage medium floats naturally (driven by density difference) over the coldest fraction, being separated by a thermocline zone. The thermocline can include either only fluid or it can incorporate a packed bed system where a low-cost filler material (granite, quartzite) is placed in the tank to store heat and reduce the amount of high-cost thermal fluid. One immediate advantage of a single tank configuration is a reduced quantity of storage materials and thus reduced tank size and cost. However, in comparison with the two-tank TES system, lower thermal efficiencies are obtained due to heat transfer interference (diffusion) between the two temperature zones. Midwest Research Institute and U.S. DOE (Contract No. EG-77-C-01-4042) have developed a floating barriers (or floating insulating membranes) of an intermediate density between the two layers in order to reduce the amount of heat transfer diffusion and maintain thermal stratification. In such technology, thermal oils and molten salts can serve as the heat transfer and storage media.

Thermocline systems that employ thermal oils are suitable for reactors operating at low to medium temperatures (~300–450°C), whereas those that employ molten salts would afford higher storage and discharge temperature capabilities. A schematic of a single-tank thermocline system is shown in Figure 3.

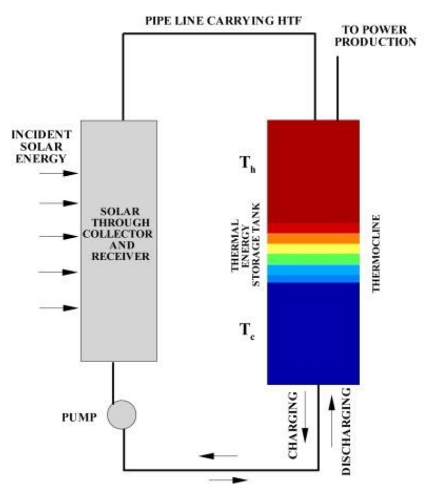

Figure 3. Schematic of a single-tank thermocline TES [12].

Note that thermocline systems can entail special size requirements and constraints, such as the need for taller tanks for improved discharge efficiencies. Molten-salt thermoclines, for example, require as much vertical space as possible in order to maximize the temperature gradients; however, in practical terms, there is often a limited height (14–16 m) that can be fabricated [13]. When compared to two-tank systems, the maximum energy withdrawal (round-trip efficiency) of thermocline systems is significantly lower for discharging energy at temperatures above 550°C: around 65% for single-tank thermocline and >99% for two-tank systems that feature a similar size and heat transfer fluid [14].

2.2.1.3 ***Hot and Cold Water Systems***

Hot and cold water thermal storage tanks are commonly used to shift cooling or heating in locations with peak demands. During off-peak hours, the source of the cooling or heating (i.e., a chiller, waste heat, or steam) is energized to circulate cold/hot water to the storage tank in order to initiate the charge cycle while simultaneously satisfying the cooling/heating needs of the associated facilities. During peak hours, the discharge cycle is initiated by deenergizing the mechanical equipment, while the storage tank serves as the source of cooling/heating. A large project regarding non-nuclear electrically powered hot and cold water storage was recently completed at Stanford University. Figure 4 shows a representative diagram of its installation. The Stanford Energy System Innovations project cut the campus's total greenhouse gas emissions by 68% and will lower the system's operating costs by $425M over 35 years [15].

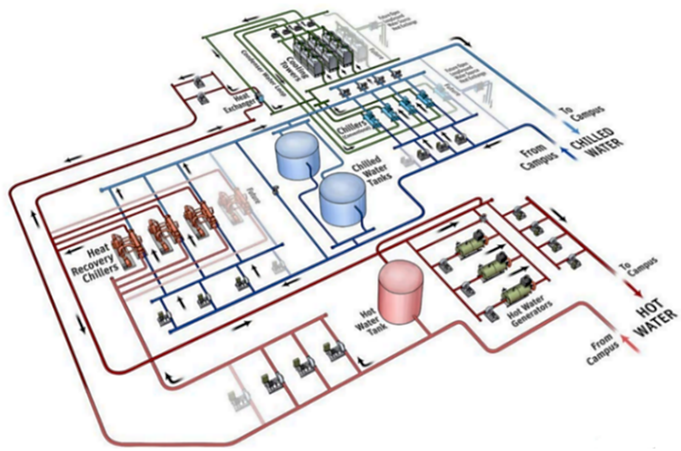

Figure 4. Schematic of Stanford University's hot and cold water system [15].

Building heating and cooling of buildings represents a big chunk of the climate equation. In and of itself, the heating of buildings uses about 32-34% of the global energy supply and is carbon intensive in the residential and commercial sectors. Due to its huge thermal mass, water can store heat efficiently and inexpensively. Hot/cold water systems can be integrated with NPPs to carry out the following functions: (1) for cooling, the storage system would use electricity to power compressor chillers in order to build up the stored cold liquid content; (2) for heating, the system would utilize heat that might otherwise be wasted, or steam discharge out of the low-pressure turbine. While this technology is expected to perform relatively poorly compared to other technologies when applied to the entire set of FOMs in this PIRT, it is included for two reasons: 1. As a proof-of-concept for the PIRT, and 2. To provide a technical database for developers who are interested in a few-selected FOMs (i.e.: custom PIRT based on subset of FOMs).

2.2.2 ***Underground Storage***

Underground energy storage systems store by pumping heat into underground locations at large depths from surface such as boreholes (30-100 m), aquifers (20-200 m), and caverns (30-60 m) [[16][17][18][19]. In most cases, water is the working fluid, forming a thermal loop to transfer heat both to and from the surrounding soil. Borehole thermal storage systems consist of drilled wells with or coaxial tubes or U-bend thermal loops that form an array of cold/hot storage media. On the other hand, aquifer thermal storage systems are based on two separate wells. In summer, water from the cold aquifer is pumped outward, used for cooling, then transferred to the warm aquifer. In winter, this process is conducted in reverse, with water from the warm aquifer being used for heating purposes prior to being returned to the cold aquifer. Figure 5 provides a schematic of an aquifer-based TES system.

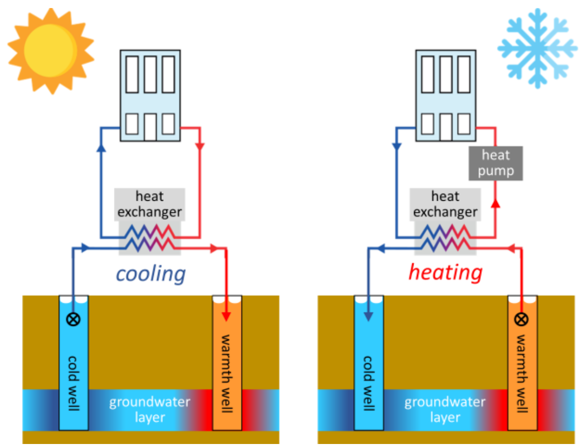

Figure 5. Schematic of an aquifer-based underground TES system[20].

Integrating this technology with a nuclear reactor is possible as long as the reservoir pressure exceeds the steam pressure. This would require a depth of at least 1,200 m to maintain sufficient saturation pressure (~575 psia) and to keep the liquid water at 250°C [21]. These conditions would allow direct steam removal from a turbine bypass stream to charge the TES system. Discharge of such a system would ideally produce saturated steam, which can be used directly in a power block or for other industrial heat applications. To prevent impurities from entering the power generation system, an intermediate heat exchanger is often needed to facilitate the heat transfer. As in the case of hot/cold TES, underground storage is expected to perform relatively poorly compared to other technologies when applied to the entire set of FOMs in this PIRT, it is included for two reasons: 1. As a proof-of-concept for the PIRT, and 2. To provide a technical database for developers who are interested in a few-selected FOMs (i.e.: custom PIRT based on subset of FOMs).

2.2.3 *Thermochemicals reactions*

In thermochemical energy storage, heat is absorbed or released through a reversible chemical reaction in which the molecular bonds are broken and reformed during an endothermic or exothermic reaction. Typically, thermochemical sotrage refers to two main processes, thermochemical reactions and sorption processes. In this work, the hydration and dehydration reversible thermochemical reactions are used as the main process to develop the PIRT for this technology. In this kind of reactions, thermal energy is stored via an endothermic reaction occurring at a trigger point and released by a reverse exothermic reaction. Figure 6 provides a schematic of the energy charge/discharge steps in a $Ca(OH)_2$/CaO-based thermochemical cell. Decomposition of $Ca(OH)_2$ into CaO is the dehydration process or energy storage step in which the water vapor is released from the hydroxide. The reaction is endothermic, with a positive reaction enthalpy. The reverse hydration reaction, in which CaO reacts with water vapor, is exothermic, with a negative reaction enthalpy, and functions as the energy discharge step.

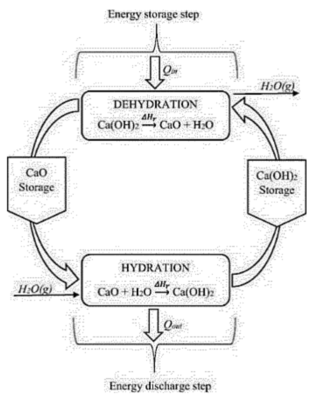

Figure 6. Schematic of $Ca(OH)_2$/CaO thermochemical energy storage [22].

Current challenges regarding thermochemical storage technologies include the high cost of such systems and the technical complexity involved in their use. One advantage they offer over latent or sensible heat storage is higher energy storage density. However, the poor cyclability of reactions prevents such technologies from quickly moving from the theoretical design or laboratory experiment stages to commercialization. Another challenge is the unavoidable complexity of the reactor design in order for the thermochemical energy storage process to work. A typical design involves multiple stages each with different material needs. Promising research has been conducted on heat removal using these kinds of systems [23][24].

2.2.4 *Latent Heat Storage – Molten Salt PCMs*

From a material science perspective, latent heat storage systems entail thermal energy being stored or released by the energy storage material while undergoing a phase transition from solid to liquid (during a charging period) or from liquid to solid (during a discharging period). This phase change occurs at near-constant temperature—a unique advantage of the latent heat storage temperature. Phase changes may also occur in the form of liquid to gas, as characterized by an even higher latent heat capacity than for a transition from solid to liquid. However, the liquid-to-gas systems have yet to be tested and evaluated at a scale similar to that undertaken for solid-to-liquid phase change systems. Other challenges for liquid-to-gas phase change systems include the unfavorable/higher pressures and impractically large storage volumes involved. For this reason, solid-to-liquid phase change systems are more popular and are being researched more heavily. In this work, the PIRT for latent heat storage is developed based on molten salts that are used as solid-to-liquid phase change material (PCM). As latent heat storage systems utilize molten salt as a PCM, the technology yield high energy storage densities, thus necessitating smaller storage sizes in comparison to sensible heat storage technologies. Figure 7 shows an example of a low-temperature latent heat storage system for heating/cooling peak load shifting at critical facilities located at the Army's National Training Center in Ft. Irwin, California [25].

Figure 7. Latent heat storage system for heating/cooling peak load shifting [25].

At the system level, latent heat storage systems consist of a storage tank (or vessel) in which heat exchangers are fully immersed in a stationary energy storage material. Because latent heat TES technology involves a solid-to-liquid phase change—or vice versa—their design and operation are more complex than sensible heat storage technology. A dedicated heat exchanger is needed to support heat transfer between the heat transfer fluid and the stationary storage medium in the tank. Although latent heat storage technologies involve certain design challenges, the huge advantages that they offer have, over the past few years, increased their prospects for rapid development and deployment.

2.2.5 ***Solid Based Sensible Heat Storage***

Solid media energy storage is a form of sensible heat storage in which thermal energy is stored by raising the temperature of a stationary solid medium such as concrete or firebrick. As with other sensible heat storage technologies, solid media energy storage requires a large-volume energy storage capacity to be effective, along with a reasonable temperature change. Compared to liquid-based sensible heat storage technologies, solid-state storage materials offer reduced capital costs while also limiting the environmental impact. Examples of thermal storage systems developed using such materials are discussed in the following subsections.

2.2.5.1 ***Firebrick***

The firebrick system, also called resistance heat energy storage, stores thermal energy generated from an electrical heater during periods of off-peak electrical demand, so that it can be used for electricity generation or industrial heat purposes during hours of peak demand. The most common materials used in firebrick storage systems are ceramics such as Al2O3, MgO, and SiC [22][26]. Ceramic firebrick can be heated to store thermal energy at 1000–1700°C. For nuclear applications, such a system could provide a very high-temperature airstream for peak heating, though further research on heat exchangers is required to support the operation of this type of system at these temperatures [27]. As with other sensible heat storage technologies, the energy storage capacity depends on the specific heat capacity and mass of the storage medium. The volumetric sensible heat storage capacity of firebrick systems falls in the range of 0.5–1.0 MWh/m^3-K, and averages about 90 kWh/m^3 [28]. A significant issue with firebrick is that it must be designed to be at least 3x the needed power capacity in order to compensate for its slow ramping time and energy interdependency [29]. Currently, the largest existing firebrick system has a maximum storage capacity of 10 MWh.

2.2.5.2 *Concrete*

Concrete TES is a simple, low-cost sensible heat storage technology in which a heat transfer fluid is transported through tubes embedded in a concrete block that serves as the energy storage medium. For high-temperature applications, thermal oils are often used as the heat transfer fluid. Concrete is a very durable material, and developers such as EnergyNest indicate that the storage life of this system exceeds 30–50 years [30]. Figure 8 shows a schematic of a single storage element and complete module by EnergyNest, both of which use its proprietary concrete material known as HEATCRETE®. Concrete storge systems are designed to be stacked interconnectedly for convenient charging/discharging purposes.

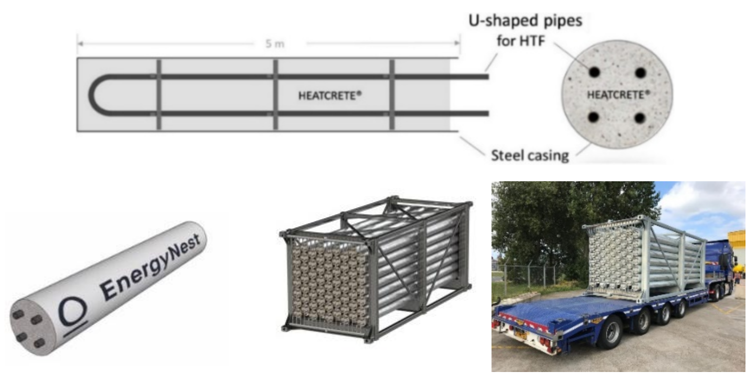

Figure 8. EnergyNest's concrete thermal energy storage element and module [31][32].

Based around the use of HEATCRETE®, the energy storage medium by EnergyNest is a concrete structure with improved thermal conductivity and heat capacity. HEATCRETE® maintains an energy storage density of 0.7 kWh/m^3-K, yielding about 88 kWh/m^3 over a temperature change of 125°C. Standard concrete has a comparable thermal storage capacity of 46 kWh/m^3 over a temperature change of 75°C. Due to the material constraints of concrete, the operating temperature range for concrete energy storage systems is restricted to <600°C [33]. A major design concern regarding concrete storage systems is the round-trip efficiencies, which are on the order of 70%. Solid media storage systems are also being investigated for use with CSP plants, hence, some of the FOMs and results of this technology are somewhat applicable to CSP systems.

2.2.5.3 *Ceramics, graphite, and alloys*

An Australian based company, MGA Thermal Pty, developed a new type of thermal storage material called Miscibility Gap Alloys. These alloys can, in a safe and easy-to-use manner, store a large amount of energy as heat. The storage system consists of stacked modular blocks of Miscibility Gap Alloys in a storage tank that is scalable from hundreds to millions of KWh of energy. According to the developer, multiple systems are being developed for a temperature range of 200–1400°C. The alloys are comprised of two components: one that melts and then disperses as fine grains, and one that remains solid in a continuous solid-media matrix. When heat is applied, the fine grains melt, storing energy in the form of latent heat, while the solid-media matrix phase holds the structure together and rapidly distributes heat. This technology is still in the early stages; however, its potential is great, as it combines the benefits of latent heat storage and solid media storage systems.

Kraftblock is another company developing a high-density TES based on solid media. Their technology involves proprietary ceramic granulate materials that can store a temperature of up to 1300°C, giving it an advantage over concrete-based TES systems. The developer has indicated that their material is compatible with a variety of heat transfer fluids, including air, flue gas, liquid salt, and even thermal oils. The system consists of standardized stackable container units of 4–60 MWh, that can be charged and discharged sequentially or run as one large module. The first demonstration pilot focused on enabling the ceramics industry to recycle process waste heat by capturing the thermal energy from flue gas [34].

In a collaboration between the University of California Berkley, Graftech, and SENER Engineering & Systems a high-temperature TES system based on graphite is being developed, thus improving the economic and technical advantages of CSPs. This technology is based on graphite blocks that have an operating temperature of over 3000°C, high thermal conductivity/diffusivity, and do not present a health hazard. Due to its abundant availability of the material, its cost can be reduced, lowering the overall cost of the TES system. The technology will be modular in design, with the storage system composed of three modules. Each module is expected to store about 250 MWht, with a large operating ΔT of about 450°C. For this design, the heat transfer fluid of choice is CO_2, as this fluid had been thoroughly researched in regard to solar receivers, has good thermal properties, can be used directly in a gas turbine, and is both cheap and readily available. The design is in its secondary stage of techno-economic analysis, and should have a significant impact once deployed with newer CSPs.

2.2.6 ***Steam Accumulators***

Steam accumulators are employed for thermal storage in various fields outside nuclear power. Their widespread use is thanks to their energy storage performance and impressive ramp/response time. In a standard system, steam accumulators store a water-steam mixture during a vessel's charging cycle, pressurizing the steam at the top of that vessel. The mixture equilibrates at saturation conditions and remains thus during charging. During discharge, the steam evacuates the vessel via an opened release valve. As the discharging cycle continues, the pressure and saturation temperature decrease, flashing additional liquid to steam that subsequently releases, as well. Figure 9 shows a schematic of a sliding pressure steam accumulator.

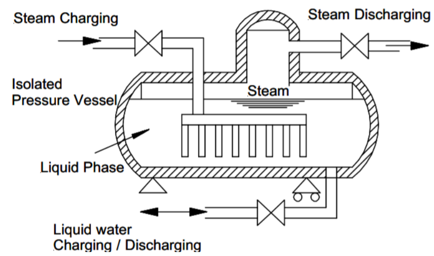

Figure 9. Schematic of a sliding pressure steam accumulator[35].

Steam accumulators store energy at around 20–30 kWh/m^3 via the pressurized, saturated water [36]. Although steam accumulators have rapid discharge capabilities with round-trip efficiencies of 60–80%, they only produce saturated steam at sliding pressures. This is detrimental because the efficiency of the power cycle decreases as more steam is released from the steam accumulator. Furthermore, steam accumulators are pressure vessels, thus they have physical constraints dictated by the operating pressure. To overcome this, the discharged steam can be superheated using electrical topping heat prior to delivering it to the power block.

2.3 Thermal Energy Storage Materials

TES technologies employ many different types of material as energy storage media. The energy density of these storage media typically varies from tens of kWh/m^3 to hundreds or thousands of kWh/m^3. Their total energy density depends on the physical density of the material, the specific heat capacity, and the nominal temperature change that the storage material would experience during the charging or discharging cycle. For this study, a comprehensive review of the various energy storage materials referenced in the literature was conducted, providing the basis for determining the potential energy storage density of a given TES technology, based on which material it uses. The maximum "or critical" temperature limit for each material is also used herein to evaluate the material's applicability within a particular advanced NPP category. Table 2 summarizes the data available in the literature on molten salts, solid media, and thermal oils.

Table 3 uses the data in Table 2 to calculate an average energy storage density for the various TES technologies, based on which materials they commonly use. Such information was used during the PIRT creation process to determine whether a given TES technology is suitable for deployment under the specific conditions pertaining to a given NPP category.

Table 2. Summary of data available in the literature on molten salts, solid media, and thermochemical materials [7][11][28][37][38][39][40][41][42][43][44][45][46][47][48].

Energy Storage Material	Melting point [ºC]	Stability limit [ºC]	Sensible heat storage [kJ/kg.K]	Latent heat storage [kJ/kg]	Density (solid) [kg/m^3]	Density (liquid) [kg/m^3]
NaNO3-KNO$_3$-NaNO$_2$ (7-49-44 mol%)	142	535	1.56	-	1640	-
LiNO3-NaNO3 (49-51 wt%)	194	-	-	-	-	-

Energy Storage Material	Melting point [ºC]	Stability limit [ºC]	Sensible heat storage [kJ/kg.K]	Latent heat storage [kJ/kg]	Density (solid) [kg/m^3]	Density (liquid) [kg/m^3]
NaNO3-KNO_3 (46-56 wt%)	222	550	1.52	-	-	1840
NaNO3-KNO_3 (60-40 wt%)	240	565	1.55	-	-	1840
$NaNO_3$	308	520	1.66	200	2257	1850
NaOH	318	-	-	165	2100	-
KNO_3	333	-	-	267	2110	-
Mg-Zn (46.3/53.7 wt%)	340	-	-	185	-	-
LiCL-KCl (45-55 wt%)	355	>700	1.2	-	-	1650
KOH	360	-	-	134	2040	-
$MgCl_2$-KCl-NaCl (60/20/20 wt%)	380	-	-	400	1800	-
Li2CO3-Na2CO3-K2CO3 (32-33-35 wt%)	397	>650	1.98	-	-	1850
$MgCl_2$/KCl (39/61 wt%)	435	-	-	351	2110	-
Al-Mg-Zn (59/33/6 wt%)	443	-	-	310	2380	-
$MgCl_2$/NaCl (32/68 mol%)	445	>700	1.15	-	2071	1920
Mg-Al (24.7/65.4 wt%)	497	-	-	285	2155	-
NaCl-CaCl2 (52/48 mol%)	513	858	1.1	178	-	-
$Mg(NO_3)_2$	526	-	-	-	-	1950
LiF-NaF-KF (29-12-59 wt%)	454	>700	1.89	-	-	2020
$Ca(NO_3)_2$	560	-	-	145	-	-
Al-Si (12/86 wt%)	576	-	-	560	2700	-
NaCl-NaF-Na2CO3 (34-13-53 WT%)	581	>750	1.91	-	-	1580
Al-Si (20/80 wt%)	585	-	-	460	-	-
$MgCl_2$	714	-	-	452	2140	-
LiF/CaF_2 (80.5/19.5 mol%)	767	-	-	790	-	-
KCl	771	-	-	353	-	-
NaCL	802	-	-	420	2160	-
Na_2CO_3	854	-	-	276	2533	-
Na_2SO_4	884	-	-	165	-	-
K_2CO_3	897	-	-	236	2290	-
Therminol®-66	-32	359	2.57	-	-	809
Dowtherm™ A	15	393	2.32	-	-	815
Concrete	-	<600	0.85	-	2200	-
Silica Firebricks	-	-	1	-	1820	-
Magnesia Firebricks	-	-	1.15	-	3000	-

Table 3. Average energy storage density for various TES technologies, based on their storage medium properties.

Material	Average Density (kg/m^3)	Average Latent Heat capacity (kJ/kg)	Average Sensible Heat storage* (kJ/kg)	Average Total Energy Storage Capacity (kJ/kg)	Average Total Energy Storage Capacity (MJ/m^3)	Average Total Energy Storage Capacity (kWh/m^3)	Type of Media
Liquid Sensible heat systems							*Liquid*
Molten salts	2100	0	194	194	407.4	113	
Thermal oils	800	0	306	306	245	68	
Water -Cold/Hot (ΔT=25ºC)	1000	0	105	105	105	29	
Water -Underground (ΔT=40ºC)	1000	0	167	167	167	46	
Solid sensible heat systems							*Solid*
Concrete	2200	0	106	106	233	65	
Firebrick	2410	0	134	134	324	90	
Latent heat systems							*Solid-to-liquid*
Molten Salts / PCMs	2100	200	194	394	827	230	
Other Systems							
Accumulators	2.2	-	-	-	72-108	20-30	liquid and gas
Thermochemicals	-	-	-	-	540-3960	150-1100	solid and liquid

*Sensible heat storage in kJ/kg is calculated based on a 125 ºC temperature difference, unless otherwise stated.

3. PHENOMENA IDENTIFICATION AND RANKING TABLE

To select energy storage technologies that are most compatible with advanced NPPs, a list of engineering, phenomena, or system decision points relevant to energy storage integration in advanced NPPs was identified. These engineering decision points are referenced herein as the PIRT analysis FOMs. Various IES FOMs were proposed in 2014 Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report [49]. The following sections discuss the 10 revised FOMs that are most relevant to advanced NPPs in this study.

3.1 Technology Readiness Level

This FOM evaluates whether the technology will be deployable in an appropriate timeframe for the advanced nuclear system of interest. The readiness or maturity of energy storage technologies referenced in this study is evaluated based on the technology readiness level (TRL), a Department of Energy standardized reference value for evaluating the commercial readiness of a given technology. The TRL indicator is then used to determine the FOM assigned for the readiness level as part of the PIRT analysis. Both, the TRL and FOM for TRL are provided in this study, wherein the FOM value is based on 0-2 scoring and the TRL is determined based on the standard 10-point scale following the TRL guide from the Technology Readiness Assessment Guide distributed by the U.S. Department of Energy [50] can be found in Appendix A-1. Some of the TES technologies considered in this study remain in development and are not currently ready for deployment. Thus, if they were to be considered for retrofitting in an existing plant—specifically, one of the current fleet of NPPs—within the next couple of years, they may not yet be technically or economically feasible for commercial deployment. However, the context of the present study relates to storage technologies considered for advanced NPPs that will not be deployed for at least several years. Therefore, these technologies may be considered under different timeline, and may be viable by the time more advanced NPPs are finally deployed. For this study, it is important that tje answer to this FOM is weighted to be more relevant to current project timelines for deploying/developing advanced nuclear reactors (i.e., ~10 years). This weighting factor is such that within the next 10 years, each technology currently rated TRL 4 or lower is expected to progress approximately two TRLs (averaging one TRL every 5 years). If currently rated TRL 5 or higher, each technology is expected to progress a total of approximately three TRLs (averaging one TRL every 3–4 years). Such assumptions are based on that fact that technologies in the TRL 2–4 range experience a phase in which fewer resources are available. This phase is known as the technology valley of death (see Figure 10) [51]. Technologies undergoing this phase tend to experience slower growth before reaching higher TRLs. It is therefore assumed that once the costs and revenues of the technologies become more certain at TRL 5–8, private investors will feel more encouraged to start moving a technology up from the valley of death. All technologies in this study resulted in an adjusted TRL of 6 to 9. A FOM of 2 is assigned for technologies with an adjusted TRL=>9, 1 for TRL= 7 to 8, and FOM of 0 is assigned for technologies with TRL<=6.

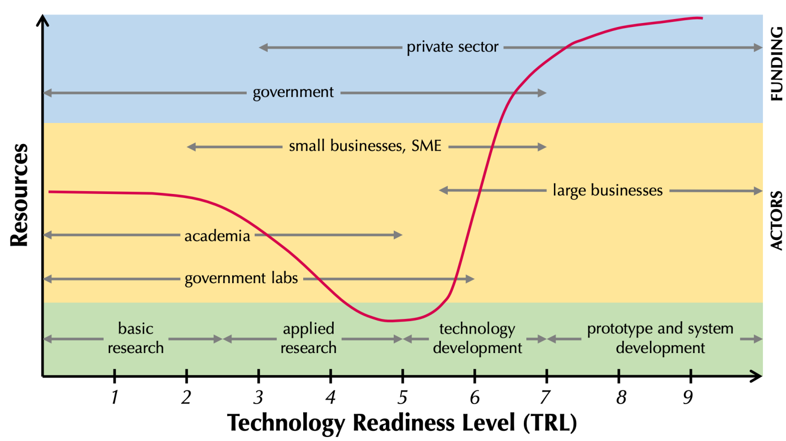

Figure 10. Resource availability as a function of technology maturation, showing the central depression or technology valley of death starting at TRL 3, when few resources are available. Adapted from Hensen et al., 2015 [35].

3.2 **Capability to Discharge High-Quality Heat**

The TES system must be capable of charging/discharging its energy capacity at a consistent temperature close to that of the advanced reactor in consideration. Storing the heat at high temperatures lowers the cost of energy, due to increased efficiency. For high-temperature advanced reactors operating at higher temperatures than do LWRs, new heat transfer media (e.g., molten salts or solid media) may be the only viable option. Further research needs to be conducted on suitable thermal transport systems, heat exchangers, and other components for containing or transporting these media. However, the current timeline for developing and deploying higher temperature advanced NPPs affords ample leeway for thermal transport systems to be developed in parallel. The readiness factor was evaluated in the previous section, whereas this FOM examines and evaluates each technology based on its ability to satisfy thermal requirements when coupled with advanced NPPs, as well as its ability to maintain elevated storage temperatures and thus elevated discharge temperatures, as well.

Any technology that can theoretically discharge its stored energy at a temperature equal to or no more than 100°C lower than the average outlet temperature of the advanced reactors of interest was assigned an FOM of 3. A technology capable of discharging its entire store at a temperature that is 100–200°C lower than the average outlet temperature of a given group of advanced reactors was assigned an FOM of 2. Due to the large number of chemical and steam manufacturing processes that correspond to temperatures of 200°C or less, an FOM of 1 was assigned to technologies that store heat at temperatures that are higher than the atmospheric boiling temperature of water, yet still relatively low (i.e., under 175°C [350°F]), regardless of the difference from the average outlet temperatures of the advanced reactors of interest. All other cases were assigned an FOM of 0 for this category.

3.3 **Energy Storage Density**

This FOM is based on the capability to offer extra energy storage at a reduced footprint—an important feature of advanced NPPs that tend to be smaller in size than the current fleet of LWRs. Microreactors, for example, are planned to be shipped in cargo containers. For that reason, any complementary hybrid energy storage system must satisfy similar size requirements, necessitating an extremely high energy density. An FOM of 0 was assigned to any system unable to store more than 75 kWht/m^3 of energy. An FOM of 1 was assigned to technologies that could be sized 75–150 kWht/m^3. An FOM of 2 was assigned to systems capable of storing 150 kWht/m^3 or more. One exception to this PIRT criteria was adopted for the small-size reactor category (i.e., microreactors), given the importance of energy storage density for this group, with an FOM of 0 being assigned to any technology with a storage density of 150 MWht/m^3 or lower. The total energy storage capacity was calculated in the same manner, assuming a temperature difference of 125°C between charging and discharging, which is a reasonable average for TES technologies coupled with NPP systems. Other technologies (e.g., a cold/hot tank) that operate at a much lower temperature difference were evaluated based on a lower, more reasonable temperature difference as reported in each relevant section.

3.4 Total Energy Storage Capacity (Thermal Capacity)

This FOM pertains to the capability to generally increase the size of smaller systems by offering high-energy storage capacities. While the size of some technologies can be increased by adding additional sub-units, either in series or in parallel, other technologies may introduce certain technical limitations. For example, steam accumulators are built in smaller units, due to the structural challenges imposed by mechanical stresses from high-pressure steam. Therefore, total storage capacity is often limited by the number of units that can be reasonably assembled together into one system. An FOM of 0 was assigned to any system not easily scalable to store energy, or that limited technical sizing to under 100 MWht. An FOM of 1 was assigned to technologies that could be sized between 100 and 400 MWht. An FOM of 2 was assigned to systems capable of storing 400 MWth or more. For the large-size NPP category (>750 MWth), an FOM of 0 was assigned if the technology could not scale up to at least 100 MWhth.

3.5 Ramp Time (Response Time)

Unlike electrochemical batteries, which can switch instantaneously from one operational mode to another, TES technologies have relatively lower ramp times when switching between modes (i.e., from charge to discharge, or from off to on). This is due to the thermal transport systems' transient characteristics, driven by the storage medium's thermal conductivity, the thermal inertia of the system components, and the control lag time. In light of the most severe reserve market restrictions, technologies with a ramp time to maximum power of 10 minutes or less were assigned an FOM of 2. Any with a ramp time of less than an hour was assigned a 1, and any with a ramp time of over an hour was assigned a 0.

3.6 Cycle Frequency

This FOM differs from ramp time in regard to the potential need and the time it takes for the technology to fully complete its charging or discharging cycle before regaining usefulness. For example, latent heat storage systems must fully transition from one phase to another before fully charging or discharging, and the average time it takes to complete each cycle ranges from hours to once per day. On the other hand, the two-tank system features separate hot and cold tanks and can switch from one mode to another on demand, even at partially charged/discharged capacity (i.e., before the system has completed its charging/discharging cycle). Cycle frequency is based on the system's capability to charge and discharge. Any system that can charge or discharge on demand was assigned an FOM of 2, whereas any system that could only cycle once per day was assigned an FOM of 1. An FOM of 0 was assigned to those systems that required even longer than that.

3.7 Realignment Frequency

This FOM considers the system's need to either wait on some phenomenon or correct a non-ideal process, thus resulting in reduced system availability. Such realignment processes are seen more often in short-cycle systems, such as in thermocline tanks whenever a thermal stratification layer widens and equalizes the entire tank, necessitating a realignment to reestablish the hot and cold sections. For cases in which no realignment was required, an FOM of 2 was assigned. If realignment was required every cycle, an FOM of 0 was assigned. An FOM of 1 was assigned for values in the middle.

3.8 Geographical Insensitivity

Geographical needs are considered because it is desired that advanced reactors with TES be deployed globally with as little redesigning as possible. An FOM of 0 was assigned to technologies that were geography-specific, while an FOM of 1 was assigned to those that were not. Additionally, an FOM of 0 was assigned if the technology of interest did not satisfy the specific geographical requirements that certain advanced reactors are designed to promote. For example, microreactors are promoted as being well suited for powering/heating domestic military bases in remote locations, and so must feature easy, scalable installation. Energy storage technologies that present additional challenges for the installation site or location (i.e.: remote locations for microreactors), were assigned an FOM of 0, despite being potentially assigned an FOM of 1 when paired with other types of advanced reactors.

3.9 Environmental Concerns

Concerns under this category include those that arise during construction, direct use, and deconstruction. An FOM of 1 was assigned to those technologies that entailed no significant environmental concerns, whereas an FOM of 0 was given to those that did. Toxic wase, source of energy storage material, and toxicity of the energy storage medium itself in the case of leak were the main parameters assessed, however a detailed assessment of the entire life cycle of each technology is beyond the scope of this study.

3.10 Minimum Turndown or Thermal Support Requirements

Any system that required heat tracing, such as maintaining temperature above certain threshold when system is on standby, or a constant supply of heat was given an FOM of 0. For example, because molten salts have relatively high liquidus temperatures, such systems must have backup heaters installed to ensure that no freezing occurs. Systems that face no concerns when heat is not constantly supplied were assigned an FOM of 1.

4. RESULTS AND ANALYSIS

This section provides a technical discussion on how each technology would perform, scoring them in terms of their ability to couple with each of the advanced NPP groups. Each technology's score is based on a qualitative and quantitative evaluation of the FOMs, and the results are then used to create a score-ranking map to identify the top TES options for each advanced NPP group.

4.1 Two-Tank Molten-Salt Systems

Experiments on two-tank molten-salt systems have reached the advanced stages, and these systems are already being used for solar power generation [52][53][54][55]. Therefore, this technology is currently at TRL 9, and was assigned a readiness FOM value of 2 for all temperature and size categories. Since molten salts are available for a wide range of temperatures, this technology is theoretically capable of discharging/charging thermal energy at nearly all temperature ranges considered in the PIRT. Figure 11 shows the possible operating temperatures of a variety of salts that correspond to an operating range of 100–450°C [56]. Table 2 and Figure 11 show various molten-salt materials suited to low, medium, and high temperatures (300–900°C). While the melting point and general thermophysical properties are well known, the stability and exact upper limits for some high-temperature molten salts (>500°C) have not yet been fully studied. The operation of sensible heat storage systems requires the storage material to remain stable at well beyond its melting point. Therefore, for coupling with NPP systems that operate at >650°C, further research and supporting information on the stability of new molten salts with melting points of 400–600°C is needed to determine their stability when exposed in liquid-molten form to temperatures of 650–900°C. An FOM value of 3 was assigned for the low- and medium-temperature ranges, while systems operating at >650°C received an FOM of 2. Because this FOM is primarily temperature-dependent, the assigned FOMs did not vary in accordance with reactor size.

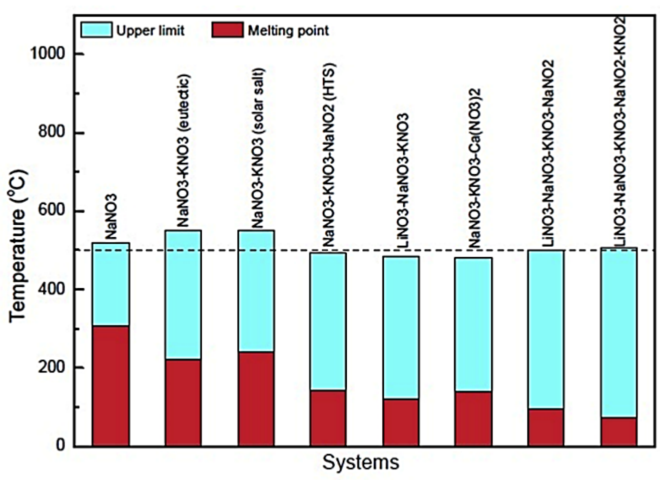

Figure 11. Operating temperature range of various salts for low-/medium-temperature energy storage [56].

In general, the energy storage density for two-tank systems is moderate, being limited by the sensible heat capacity of the selected material. Since molten salts have an average energy density of 113 kWh/m^3 (based on a 125°C temperature difference), these systems were assigned an FOM of 1 for energy density for all temperatures and sizes—except for the microreactor category, for which an FOM of 0 was assigned, as higher energy storage densities are necessary in order to align with the small-size requirement and compactness for this subgroup. Since two-tank systems are easily scalable and systems operating at +400 MWh already exist [57], an FOM of 2 for capacity was assigned for all temperature and size categories.

Two-tank molten-salt storage systems can ramp up quickly enough for the TES to respond and achieve maximum power at anywhere between 10 minutes and an hour due to the natural transient characteristic of its thermal transport systems. Because the same FOM for ramp time was applied regardless of the temperature and size category, an FOM of 1 was assigned across the board. By their very nature, sensible heat storage systems can cycle as frequently as necessary, with few realignment requirements no matter the size or temperature range. Thus, FOMs of 2 and 1 were assigned in regard to cycle and realignment frequencies, respectively. Two-tank systems are geographically insensitive, as they are always above ground for NPPs, regardless of operating temperature or size; therefore, they were assigned an FOM of 1.

Molten salts entail no environmental concerns, thus earning an FOM of 1 for this section. Molten salts have high liquidus temperatures around which they remain stable. However, the operation of sensible heat storage systems requires pushing the material well beyond its melting point. As already indicated, reactors operating at high-temperature ranges (>650°C) will require molten salts with melting points of 450–600°C in order to remain stable at temperatures of 650–900°C. Hence, molten salts operating in sensible heat storage will require careful consideration and monitoring to ensure that the system temperature does not exceed their critical temperature. Such supporting information is not yet available, so, for the minimum turndowns and thermal support needs, an FOM of 1 was assigned for both the low- and medium-temperature ranges, while an FOM of 0 was assigned for the high-temperature ranges.

Evaluation of the two-tank molten-salt systems revealed PIRT scores of 14–17, as shown in Table 4.

Table 4. Two-tank molten-salt system PIRT scoring table.

[redacted]									
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	2	2	2	2	3	2	2	2	2
[redacted]									
Energy Storage density (system size)	0	1	1	0	1	1	0	1	1
[redacted]									
Ramp time (response time)	2	2	2	2	2	2	2	2	2
[redacted]									
Realignment frequency	1	1	1	1	1	1	1	1	1
[redacted]									
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]									
Sum	15	16	16	15	17	16	13	14	14

4.2 Two-Tank Thermal-Oil Systems

The two-tank systems, using thermal oils, scored identical FOM values as the molten-salt systems for the following categories: readiness level, total energy storage capacity, ramp time, cycle frequency, realignment frequency, and geographical insensitivity. The difference between the thermal-oil and the molten-salt two-tank systems appears in regard to four categories. First, thermal oils have a lower temperature limit (critical operating temperature) than molten salts, and are only compatible with reactors that operate at low temperatures (<350°C). Therefore, an FOM of 0 was assigned for the medium- and high-temperature ranges, and an FOM of 3 was assigned for reactors operating at low temperatures. Secondly, the specific heat of thermal oils is lower than that of molten salts, yielding 68 kWh/m^3 of total energy storage capacity for storage systems operating under a temperature difference of 125°C. Therefore, an FOM of 0 was assigned for energy storage density. Thirdly, thermal oils are of greater environmental concern than molten salts, due to post-use leakage and deposition. Batuecas et al. evaluated the use of synthetic oil from an environmental point of view by using the life cycle assessment techniques and showed greater impacts in the synthetic oil case than molten salts [58]. The study showed that the Global warning impact (GWP100) of thermal oils to be >3 times higher than molten salts (10 vs 3) in a 1 kg of material. In addition, results showed that every thermal oil impact category possesses the highest environmental impacts when compared to all other molten salts studied. So, an FOM of 0 was assigned for this category. Fourth, the optimal operating temperature range of thermal oils does not impose any additional turndown requirements for the low-temperature category. Therefore, an FOM of 1 was assigned for the low-temperature category, whereas an FOM of 0 was assigned for the medium- and high-temperature categories—with which the technology is incompatible anyway.

Evaluation of the two-tank thermal-oil systems revealed PIRT scores of 9–13, as shown in Table 5.

Table 5. Two-tank thermal-oil system PIRT scoring table.

	[redacted]			[redacted]			[redacted]		
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	2	2	2	2	2	2	2	2	2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Energy Storage density (system size)	0	0	0	0	0	0	0	0	0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Ramp time (response time)	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Realignment frequency	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Environmental concerns	0	0	0	0	0	0	0	0	0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sum	13	13	13	9	9	9	9	9	9

4.3 **Thermocline Molten-Salt Systems**

Experiments with thermocline molten-salt systems have reached the advanced stages, and stratified water storage is already being conducted in this manner [7][59]. Therefore, this technology is currently at TRL 5 and has an adjusted TRL of 8, hence is assigned a readiness FOM value of 1 for all temperature and size categories. Molten salts are compatible with almost all storage temperatures. However, as discussed in greater detail in Section 4.1, the challenge with sensible heat storage systems lies in the operational strategy, which pushes the storage material well beyond is melting point to store sensible heat. For that reason, the applicability of molten salts as a sensible heat storage medium for very high-temperature reactors is questionable. Additionally, thermocline systems rely on a single tank for the charge/discharge cycle; therefore, the output temperature and heat rate of a thermocline system decreases as more hot fluid is discharged and replaced by colder fluid toward the end of the discharge cycle [60][58][61]. For these reasons, in regard to the capability to discharge high-quality heat, an FOM of 2 was assigned for low- and medium-temperature ranges, while an FOM of 1 was assigned for systems operating at >650°C.

The storage density of thermocline molten salt systems is similar to that of any other sensible heat storage system that uses molten salts have an average energy density of 113 kWh/m^3, so an FOM of 1 for energy density was assigned for all temperature and size categories—except for the microreactor category, for which an FOM of 0 was assigned, as high-energy storage densities are necessary in order to align with the small-size requirement and compactness for this type of reactor. As a sensible heat storage system, the energy capacity of thermocline systems solely depends on vessel size. Since no mention of restrictive limits has been made by the developers or in the literature, an FOM of 2 was assigned for total energy storage capacity.

Thermocline molten-salt storage systems can ramp up quickly enough, as the system discharges via pumped fluid, and they can respond and achieve maximum power anywhere between 10 minutes and an hour. Since the same FOM for ramp time was applied regardless of temperature and size category, an FOM of 1 was assigned for this category. Ideally, a thermocline system should be able to cycle as often as necessary, so an FOM of 2 was assigned for this category. However, thermocline degradation causes significant issues in these systems and must be frequently addressed, causing an FOM of 0 to be assigned for realignment requirements [59]. And because the system is a tank built onsite and entails no geographic needs, an FOM of 1 was assigned in this regard.

Molten salts entail no environmental concerns, thus earning an FOM of 1 in this aspect. Molten salts have high liquidus temperatures, around which they remain stable; however, the operation of sensible heat storage systems requires pushing the material well beyond its melting point. As has already been indicated, reactors operating at high-temperature ranges (>650°C) will require molten salts with melting points of 450–600°C in order to remain stable at temperature ranges of 650–900°C. Hence, for minimum turndowns or thermal support needs, an FOM of 1 was assigned for the low- and medium-temperature ranges, while an FOM of 0 was assigned for the high-temperature ranges.

Evaluation of the thermocline molten-salt system revealed PIRT scores of 9–12, as shown in Table 6.

Table 6. Thermocline molten-salt system PIRT scoring table.

[redacted]									
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	1	1	1	1	1	1	1	1	1
[redacted]									
Energy Storage density (system size)	0	1	1	0	1	1	0	1	1
[redacted]									
Ramp time (response time)	1	1	1	1	1	1	1	1	1
[redacted]									
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]									
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]									
Sum	11	12	12	11	12	12	9	10	10

4.4 Thermocline Thermal-Oil Systems

The thermocline systems, using thermal oils, scored identical FOM values as the molten-salt systems for the following categories: readiness level, total energy storage capacity, ramp time, cycle frequency, realignment frequency, and geographical insensitivity. Thermocline thermal-oil systems and thermocline molten-salt systems differ in regard to four categories. First, thermal oils have a lower critical temperature and are only compatible with reactors operating at low temperatures (<350°C). Thus, for high-quality heat discharge capability, an FOM of 0 was assigned for the medium- and high-temperature ranges, and an FOM of 2 was assigned for reactors operating at low temperatures. Secondly, thermal oils' specific heat is relatively low, yielding 68 kWh/m^3 of total energy storage capacity for a storage system operating at a temperature difference of 125°C between charge and discharge. Therefore, an FOM of 1 was assigned for energy storage density. Thirdly, thermal oils entail some environmental concerns due to post-use leakage and deposition, so an FOM of 0 was assigned in this category. Fourth, because the optimal operating temperature range of thermal oils does not impose any additional turndown requirements for the low-temperature category, an FOM of 1 was assigned for the low-temperature category, while an FOM of 0 was assigned for the medium- and high-temperature categories—for which they are incompatible anyway.

Evaluation of thermocline thermal-oil systems revealed PIRT scores of 7–11, as shown in Table 7.

Table 7. Thermocline thermal oil system PIRT scoring table.

[redacted]									
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	1	1	1	1	1	1	1	1	1
[redacted]									
Energy Storage density (system size)	0	1	1	0	1	1	0	1	1
[redacted]									
Ramp time (response time)	1	1	1	1	1	1	1	1	1
[redacted]									
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]									
Environmental concerns	0	0	0	0	0	0	0	0	0
[redacted]									
Sum	10	11	11	7	8	8	7	8	8

4.5 **Hot/Cold Water**

Now fully developed, hot and cold water storage technology is commonly being used to shift cooling or heating in residential, commercial, and industrial facilities with peak demands. A large amount of experience has been amassed in using these systems (TRL>9), so an FOM of 2 was assigned for readiness. This technology is incompatible with high-pressure steam from nuclear reactors for direct charging, and its water discharge temperature is limited, at most, to a few degrees below the atmospheric boiling temperature of water (<100°C). Integration with nuclear is limited to stored cold water employed by buildings for cooling applications using an electric chiller, or hot water that serves as a heat source by being drawn out of a low-pressure turbine. This low level of compatibility with high-quality steam leads to an FOM of 0 for the capability to discharge high quality heat.

Water has a relatively high specific heat density compared to other materials. The proposed FOM criterion for this category suggests using the energy density stored across a 125°C temperature difference to determine the FOM value. However, because they are used for heating/cooling applications, cold/hot water tanks often operate at a much smaller temperature difference compared to other storage systems. Thus, their energy density is often calculated based on a 10–40°C temperature difference before the hot/cold water tank is considered either fully discharged or charged. At a more reasonable temperature difference ($\Delta T = 25°C$) for these systems, the average energy density is ~29 kWh/m^3, thus an FOM of 0 was assigned. Because cold/hot water tanks are scalable and systems operating at +1 GWh already exist [62][63], an FOM of 2 for capacity was assigned for all temperature and size categories.

Cold/hot water tanks ramp quickly and can achieve maximum power in under an hour, but require more than 10 minutes, due to the natural transient characteristics of its thermal transport systems. In this case, the FOM for ramp time does not depend on temperature or size, so an FOM of 1 for this category was assigned for all temperature and size ranges. By their very nature, because sensible heat storage systems need to be fully charged for an optimum discharge operation (i.e.: hot water is supplied at optimum temperature), they do not allow for switching from one mode to another on demand (i.e.: during the mid of the charge cycle, before it is 100% complete). Hence, they often operate based on daily charge cycling. Therefore, an FOM of 1 was assigned in this regard. Realignment requirements depend on the tank formations. Cold/hot water stratified tanks have a temperature gradient layer that naturally degrades as a function of time, creating a tank that is in no way stratified and requires an engineering design different than the current one [64]. Thus, an FOM of 0 was assigned for realignment.

Cold/hot water tanks are geographically insensitive and installed above ground for all installations. However, coupling them with microreactors might introduce some challenges in remote locations, as most cold/hot water tanks are built onsite due to their large size requirements, which originate from their low energy density. Building the tanks onsite may not always be an option for the types of remote locations that microreactors are expected to serve. Therefore, an FOM of 1 was assigned for all temperature and size categories except the small-sized reactor category (i.e., microreactors), for which an FOM of 0 was assigned. Because these systems are environmentally friendly, an FOM of 1 was assigned for environmental concerns. No minimum turndown requirement is placed on the system, so the FOM for this category is a 1.

Evaluation of cold/hot water tank systems reveals PIRT scores of 8 or 9, as shown in Table 8.

Table 8. Cold/hot water tank PIRT scoring table.

	[redacted]								
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	2	2	2	2	2	2	2	2	2
[redacted]									
Energy Storage density (system size)	0	0	0	0	0	0	0	0	0
[redacted]									
Ramp time (response time)	1	1	1	1	1	1	1	1	1
[redacted]									
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]									
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]									
Sum	8	9	9	8	9	9	8	9	9

4.6 Underground Energy Storage Systems

The underground energy storage systems evaluated in this section include boreholes and aquifers. Because they share similar advantages and have nearly the same limitations, they are evaluated in tandem in this study. These underground storage systems, now fully developed (TRL>9), are currently installed in residential and commercial buildings to provide cold and warm seasonal thermal masses. Therefore, an FOM of 2 was assigned for readiness level. All underground storage systems use liquid water as the energy storage medium. Though possible to use high temperatures/pressures to charge these systems, the current systems operate under ionospheric pressure; hence, this technology is limited by the atmospheric boiling point of water [65][66]. Any interface with steam produced by nuclear-generated heat would require new heat exchange methods. Thus far, experience does not indicate the possibility of high storage temperatures/pressures, so an FOM of 0 was assigned for compatibility to discharge high-quality heat.

Water has an excellent specific heat capacity and is an ideal energy storage material for low-temperature sensible heat storage. Based on a reasonable temperature difference of 40°C between charge and discharge, the average energy density of these seasonal storage systems is 58 kWh/m^3 [67]. Therefore, an FOM of 0 was assigned for this category for all temperatures and sizes. The storage size for aquifer and borehole systems can be quite large, and it is often the case that no technical limitation is placed on the system size. Therefore, an FOM of 2 was assigned for total energy storage capacity.

The ramp time for these systems is not estimated to be very high. Underground energy storage systems are designed with seasonal storage in mind, and the ability to ramp up to maximum power within minutes or hours was never a priority, thus meriting an FOM of 0 for ramp time. Similarly, these systems are designed to cycle on a seasonal basis and cannot charge/discharge on demand, or even on a daily basis [68]. Therefore, an FOM of 0 was assigned for cycle frequency. The location of the boreholes and/or aquifers is identified and evaluated prior to commissioning. Hence, realignment requirements are minimum, as the system is always available in a given season, resulting in an FOM of 1 for this category. Underground storage systems have geographical sensitivity, resulting in an FOM of 0 for geographic insensitivity. Underground siting causes large intrusions to groundwater, impacting its environmental score and leading to an FOM of 0 [69]. However, these systems are reliable, relatively simple to operate, and can continue operating without constant input, resulting in an FOM of 1 for minimum turndown [70].

Evaluation of underground energy storage systems reveals PIRT scores of 6, as shown in Table 9.

Table 9. Underground energy storage system PIRT scoring table.

	[redacted]								
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	2	2	2	2	2	2	2	2	2
[redacted]									
Energy Storage density (system size)	0	0	0	0	0	0	0	0	0
[redacted]									
Ramp time (response time)	0	0	0	0	0	0	0	0	0
[redacted]									
Realignment frequency	1	1	1	1	1	1	1	1	1
[redacted]									
Environmental concerns	0	0	0	0	0	0	0	0	0
[redacted]									
Sum	6	6	6	6	6	6	6	6	6

4.7 **Thermochemical Reactions**

Because thermochemical energy storage systems that are based on hydration and dehydration reactions remain in the small-scale component laboratory stages that align with TRL 4 and adjusted TRL of 6 [71][71][73][74], an FOM of 0 was assigned for adjusted readiness level. Most of the research focuses on low-temperature applications, and the uncertainly involved in thermochemical systems currently makes it difficult to determine whether these systems will align with low-temperature nuclear systems. Medium- and high-temperature systems are even more difficult to predict; therefore, for compatibility to discharge high-quality steam, an FOM of 1 was assigned for low-temperature nuclear systems, and an FOM of 0 was assigned for medium- and high-temperature systems.

Thermochemical materials have an energy storage density higher than that of any of the other sensible and latent heat technologies. In the literature, the average energy density shows a very broad range of 150–1110 kWh/m^3 [46][47][48], so an FOM of 3 was assigned for energy storage density. Aided by the high energy density, designing large-capacity thermomechanical systems should be possible; however, most previous experiments on these systems involved less than a few MW [71][73][75]. This leaves uncertainty regarding the systems' ability to scale to large (>400 MWth) NPP systems. Therefore, an FOM of 1 was assigned for the small- and medium-size NPP categories, and an FOM of 0 was assigned for the large NPP category.

Ignoring that the readiness-related technical challenges are evaluated in a separate category, and that continued research efforts could reveal the possibility of better response times, the current data show the rate of the hydration/dehydration reaction to be very slow [76]. Thus, an FOM of 0 was assigned for ramp time. Additionally, slow hydration rates impact the cycle frequency, as it currently takes over a day to complete a full charge/discharge cycle [23], leading to an FOM of 0 in this regard. Thermochemical materials entail reversibility concerns, leading to an FOM of 0 for realignment frequency. Thermochemical reactors are not geographically sensitive, and the materials are considered environmentally friendly, leading to an FOM of 1 in both these categories.

Finally, in a typical thermochemical reactor system, products and reactants are kept in separate vessels, while the reaction requires continuous monitoring and heat tracing to maintain an ideal operational temperature. Thus, an FOM of 0 was assigned for the turndown and thermal support requirement.

Evaluation of the thermochemical energy storage systems reveals PIRT scores of 4 to 6, as shown in Table 10.

Table 10. Thermochemical energy storage system PIRT scoring table.

[redacted]									
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	0	0	0	0	0	0	0	0	0
[redacted]									
Energy Storage density (system size)	2	2	2	2	2	2	2	2	2
[redacted]									
Ramp time (response time)	0	0	0	0	0	0	0	0	0
[redacted]									
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]									
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]									
Sum	6	6	5	5	5	4	5	5	4

4.8 **Latent Heat Storage - Molten salt PCMs**

Latent heat storage systems have an attractive energy storage density and a favorable passive constant (or nearly constant) discharge temperature. To determine if any of the latent heat storage concepts are technically superior to other technologies, the technology must achieve an advanced stage of technical maturity, undergo comparable comprehensive testing and analysis, and acquire significant operating experience under realistic conditions for NPPs. Currently, low-temperature latent heat storage systems are already commercialized and have been commissioned in various residential, commercial, and industrial facilities for heating and cooling peak load shifting [25][77][78] . Companies such as CALMAC, Ice Energy Technologies Inc, and Baltimore Aircoil Company offer ice-based latent heat storage systems for low-temperature HVAC applications (0–15°C). Phase Change Energy Solutions, Inc offers PCM-based latent heat storage systems and metallic heat exchangers for slightly higher temperature applications (e.g., HVAC cooling/heating and waste heat recovery for industrial systems) in the range of 15–120°C.

While latent heat storage systems that operate at these temperatures are fully developed and now commercially available, latent heat storage systems for higher temperatures NPPs may cause additional challenges for developers. At the material science level, several molten salts have already been studied and are very well documented in the literature. At the system engineering level, despite its readiness for room-temperature applications and other types of industrial systems, latent heat storage systems for high-temperature applications remain at the laboratory scale for validation in relevant environments, thus aligning with TRL 5 and adjusted TRL of 8. Therefore, an FOM of 1 for readiness level was assigned for this technology.

Several latent heat storage materials feature melting points and critical operating temperatures that are appropriate for low-, medium-, and even high-temperature applications [79][80][81][82][83]. Some examples are listed in Table 2. The main challenge with latent heat energy storge technology is to test the storage materials in a well-scaled system with suitable heat transport components including heat exchangers. While some advanced reactors are not expected to be ready for deployment until 10 years from now, this timeline offers generous leeway for latent heat storage technology to become fully characterized and developed by then. For very high-temperature NPPs, latent heat storage systems can be used at temperatures around the melting point of the storage material—thus initiating a phase transition—and are not expected to operate well beyond this melting points, unlike with sensible heat storage. Thus, materials used as a latent heat storage medium are stable per the typical operating principles of latent heat storage systems. Given the materials currently available and the performance metrics involved, if the design challenges are overcome, latent heat storage technologies should be very compatible with low-, medium-, and high-temperature steam discharge. An FOM value of 3 was assigned for the low- and medium-temperature ranges. Because further engineering work is still needed on heat exchangers design for the technology to operate at temperatures of 650–900°C, the technology received an FOM of 2 for high-temperature category. Because this FOM is primarily temperature-dependent, the assigned FOMs did not vary in accordance with reactor size.

Energy capacity should not be an issue, as the total energy density of high-temperature molten salts and other PCMs is very high when the latent heat component is added to the sensible heat component. Table 3 shows that the average energy density of latent heat storage materials is the highest among all the technologies evaluated in this study (apart from thermochemical storage), yielding about 230 kWh/m^3. Therefore, an FOM of 2 was assigned for capacity. The system energy density is also attractive for the microreactor group, which requires compact, modular systems that are easily transportable and feature ample storage with a small footprint, thereby earning the same FOM for this group—something the other technologies failed to achieve. The system should be scalable, and with higher energy storage density, it can be scaled well beyond 400 MWhth, thus achieving an FOM of 2 for this category.

For latent heat storage systems, the ramp time to full power depends on how the heat is moved by the heat transfer fluid, and the system response is estimated at anywhere from 10 minutes to an hour [37][84][85]. Thus, an FOM of 1 was assigned Low-temperature latent heat storage systems have mainly been used to switch from one mode to another on demand. The same is expected for systems operating in high-temperature applications. Unlike single-tank systems or thermocline systems, heat losses or partial charge/discharge should not impact the system's ability to switch operational modes as the material remains at constant temperature (phase transition temperature) during the entire liquid-to-solid or solid-to-liquid phase change process. Systems that can switch on demand were assigned an FOM of 2.

The method of evaluating the realignment conducted between cycles must itself be carefully evaluated. The assumption that the main challenge with latent heat storage is material expansion and contraction (volume change) is often a misleading oversimplification when generalized to include high-temperature latent heat storage materials or molten salt phase-change materials. The water/ice (known as salt hydrates) in low-temperature latent heat storage systems expands in solid phase during the liquid-to-solid (solidification) phase transition process, putting serious mechanical stresses on the heat exchanger, vessel, and other components. On the other hand, molten salts when used as a high-temperature latent heat storage material, have lower physical densities during their molten phase than during their solid phase. Therefore, unlike other lower temperature heat storage materials, molten salts tend to shrink during solidification and expand only when transitioning to a molten state, causing much less stress thanks to the mobility of the liquid phase during expansion, as compared to the solid phase expansion that is experienced with other materials. On the other hand, molten salts have relatively low thermal conductivity, leading to localized phase change conditions at the surface of the heat exchanger (tubes or plates). This phenomenon is known as the phase change front phenomena or PCM self-shielding, in which the layer of material at the surface of the heat exchanger (phase change front) melts sooner than the material farther away from the surface. Hence, a discharged thin film/layer forms at the surface, reducing the overall heat transfer coefficient. This results in a fully charged/melted film that acts as an insulation layer with a thermal conductivity (0.4–0.6 W/m K) that is ~50% lower than the uncharged solid material (1 W/m K) [86][87]. The same happens during the charge cycle, when a solid/frozen layer of the material forms at the surface (most obvious at larger plate-to-plate or tube-to-tube distances). Some studies have identified ways to overcome this phenomenon by optimizing the plate-to-plate (or tube-to-tube) distance of the heat exchanger. While certain engineering solutions address these issues, high-temperature latent heat systems continue to experience certain phenomena or correct certain non-ideal processes, potentially leading to reduced system availability toward the end of the charge/discharge of every cycle, resulting in an FOM of 0 for this category.

Latent heat storage systems are insensitive to a specific geography, and given their high energy density, could be shipped or built onsite. Thus, an FOM of 1 was assigned. High-temperature latent heat storage systems use molten salts and entail no environmental concerns, earning an FOM of 1 for this section. Because in latent heat storage systems the storage medium must, by nature, be designed to operate while in the solid or liquid phase, there is no danger to the system if the system overcools, and no minimum turndowns. For NPPs operating at very high temperatures (>800°C), the critical temperature of most latent heat storage materials beyond 800°C has yet to be determined, and an additional thermal support system may be needed to prevent the system from exceeding a certain threshold temperature during the charge cycle. Thus, an FOM of 0 was assigned for high-temperature reactors, and a 1 for the medium- and low-temperature categories.

Evaluation of the latent heat storage technology reveals PIRT scores of 12-14, as shown in Table 11.

Table 11. Latent heat energy storage PIRT scoring table.

	[redacted]			[redacted]			[redacted]		
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Energy Storage density (system size)	2	2	2	2	2	2	2	2	2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Ramp time (response time)	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sum	14	14	14	14	14	14	12	12	12

4.9 Solid Based Sensible Heat Storage

The solid media energy storage systems evaluated in this section include concrete, firebrick, ceramics, graphite, and alloys. Because they mostly share similar advantages and have nearly the same limitations, they are evaluated together herein. However, being the most promising solid based sensible heat technology for coupling with NPPs, it is noted that concrete is the primary technology under consideration in this category.

The readiness level varies from one technology to another. Concrete energy storage is slowly moving up from TRL 5, as the technology is transitioning from the laboratory-scale level to the demonstration level, with some pilot-scale installations having been reported by a few developers over the past few years. Taking HEATCRETE® as a refence, EnergyNest completed a 1-MWhth field pilot at the Masdar Institute of Science and Technology in 2015, and 4.1-kWh scaled testing in 2018 [88]. Firebrick thermal energy storage was evaluated at a slightly lower TRL of 3, due to a lack of relatable technology relative to other thermal storage technologies. Other solid media storage materials such as ceramics, graphite, and alloys remain in an early stage and are slowly moving from component and system validation in a laboratory environment to analytical and experimental proof of concept—keeping them at the edge of TRL 2 or 3. Thus, based on an TRL of 4-5 (adjusted TRL of ~8) for first movers in solid media technologies, an FOM of 1 was assigned for adjusted readiness level. Experiments and developers have shown that most solid media should be able to charge via direct usage of low- and high-temperature steam, without needing to depressurize or preliminarily cool the steam. However, discharge cycles often entail a reduction in discharge power and quality heat [89][31], hence these systems are more effective when charged at higher steam temperatures. Systems that use resistance heaters (e.g., firebrick) as a source of heat are typically operated to 1000–1200°C and could easily achieve high-quality heat at such temperatures. However, their connection point is electrically (instead of thermally) coupled, leading to large technical challenges in coupling the technology for all temperature ranges and NPP types [90]. Concrete TES systems have technical limitations of 600 °C for their maximum operating temperature, and a power reduction is present during discharge [30][31]. Thus, for the Low- and medium-temperature ranges, a moderate FOM of 2 was assigned high quality heat. An FOM of 1 was assigned for the high temperature range.

The energy storage capacity of solid media is 60–90 kWh/m^3, at an average temperature change of 125°C [91]. Thus, an FOM of 1 was assigned in this regard for all temperature and size categories—except for the microreactor category, in which an FOM of 0 was assigned, as higher energy storage densities are required in order to be in alignment with the compactness requirements for this reactor type. Solid-media storage systems are often promoted as modules, and given the simplicity of the designed modularity, they can easily be scaled to gigawatts of storage capacity [92]. Concrete storage systems are promoted by developers as having a response time of only a few minutes [93]. Electrically heated systems such as firebrick can also ramp up quickly, thus an FOM of 2 was assigned for this category [29].

Realignment events are not required, especially since these systems are more likely to operate for long cycles. For example, firebrick has shown discharge times of over a full day [90]. Therefore, FOMs of 2 and 1 were assigned for cycle frequency and realignment frequency, respectively. Solid-media storage systems are insensitive to a specific geography, and are compatible with microreactors. Many developers are offering their energy storage systems in small, easily transportable modules that require no onsite construction. Therefore, an FOM of 1 was assigned for this category. Finally, most solid-media energy storage materials are not environmentally taxing, so an FOM of 1 was assigned to this category. Finally, this technology has no minimum heat transfer fluid temperature, and its maximum operating temperature is also compatible with very high-temperature NPPs, meriting an FOM of 1 for minimum turndown and thermal support needs.

Evaluation of solid-media storage systems reveals PIRT scores of 12 to 14, as shown in Table 12.

Table 12. Solid-media energy storage system PIRT scoring table.

	[redacted]			[redacted]			[redacted]		
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Energy Storage density (system size)	0	1	1	0	1	1	0	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Ramp time (response time)	2	2	2	2	2	2	2	2	2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Realignment frequency	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sum	13	14	14	13	14	14	12	13	13

4.10 Steam Accumulators

Steam accumulator technology is already at an advanced stage and has long been in use, coupled with boilers across various industries [28]. Thus, this technology is evaluated to be TRL 9, and was assigned an FOM of 2 for readiness level. High-temperature steam is usable as input in steam accumulators, and charging with steam in low-, medium-, or high-temperature NPPs is technically possible. However, during discharge, accumulators only produce saturated steam at sliding pressures, and the efficiency of the power cycle decreases as more steam is released from the steam accumulator [31]. To accommodate for pressure loss toward the end of the discharge cycle, accumulators must often be superheated using electrical topping heat before delivering the steam to the power block. Furthermore, their maximum temperature is limited by the critical point of saturated water (374°C, 221 bar), and their round-trip efficiencies are 60–80%. Based on this, an FOM of 1 was assigned for the low-temperature NPP category, and a 0 was assigned to the medium- and high-temperature NPP categories.

Steam accumulators store energy at around 20–30 kWh/m^3 via the pressurized and saturated water, so an FOM of 0 was assigned for energy storage density. Most steam accumulators are not built very large due to the structural challenges and mechanical stresses caused by high-pressure steam. Therefore their total storage capacity is often limited by the number of units that can be reasonably assembled together into one system. An energy density of 20–30 kWh/m^3, and a volume of10,000 gallons (about 38 m^3 of internal volume per unit) leads to 0.76–1.14 MWh per unit [36]. Hence, it can be concluded that steam accumulators are better suited for coupling with small-to-medium-sized NPPs with energy storage capacities of less than 400 MWh-th. Thus, an FOM of 1 was assigned for energy storage capacity for small- and medium-sized systems, and a 0 was assigned for large-sized systems.

Steam accumulators have rapid discharge capabilities and have been proposed as a type of supporting mechanics to other storage concepts with larger storage capacities and longer start-up procedures [31][94]. This technology can respond and provide maximum power within 10 minutes, so an FOM of 2 was assigned for the ramp time category.

Because steam accumulators can initiate steam discharge very quickly by opening the steam release valve, their operational principles and mechanics are straightforward, and there are effectively no concerns of losing the ability to cycle on demand [95]. Thus, an FOM of 1 was assigned for cycle frequency. To ensure proper pressure inside the vessel, steam accumulators require that cooled water be periodically injected, impacting their realignment frequencies. Thus, an FOM of 0 was assigned for this category. Steam accumulators score an FOM of 1 for geographic insensitivity, environmental concerns, and minimum turndown rate, as these categories are of no concern. Accumulators are shipped on trucks for installation and can thus be located anywhere. They are made of standard steel materials and do not require trace heating to maintain pressure during down time.

Evaluation of steam accumulator energy storage technology reveals PIRT scores of 8 to 10, as is shown in Table 13.

Table 13. Steam accumulator energy storage PIRT scoring table.

[redacted]									
PIRT Criteria	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
Readiness level	2	2	2	2	2	2	2	2	2
[redacted]									
Energy Storage density (system size)	0	0	0	0	0	0	0	0	0
[redacted]									
Ramp time (response time)	2	2	2	2	2	2	2	2	2
[redacted]									
Realignment frequency	0	0	0	0	0	0	0	0	0
[redacted]									
Environmental concerns	1	1	1	1	1	1	1	1	1
[redacted]									
Sum	10	10	9	9	9	8	9	9	8

5. CONCLUSIONS

This study analyzed 10 thermal energy storage technologies, with 10 specific engineering questions (discussed in detail) regarding the potential for these technologies to be integrated with advanced nuclear system technologies. A specific evaluation was provided for nine groups of advanced nuclear systems in a 3x3 matrix consisting of low-, medium-, and high-temperature NPP systems, each divided into three subgroups pertaining to small-, medium-, and large-sized systems. Currently, many of these energy storage technologies are also being investigated for use with concentrating solar power (CSP) plants, and when the plant temperatures and sizes are close the classification used for NPPs in this study, the result gives readers a point of reference applicability on the applicability of these TES to CSP for the purpose of power generation. A ranking tool identified the important characteristics of thermal storage and ranked each of these technologies accordingly. This study includes pertinent information on a range of energy storage technologies. Not only does it rank various TES systems that are well-suited for integration with advanced NPPs, but it also compiles information on system maturity, relevant performance, and research gaps—information usable to further enhance these technologies.

Table 14 summarizes the information gathered in this study in order to generate a few top-level technology recommendations for each NPP category based on their scores and development projection in the near-term future as it applies to advanced nuclear reactors evolution. Two-tank molten-salt, latent heat storage system, and solid-media storage system are ranked highly. It can be concluded that type of technology best suited for a developer's individual reactor type greatly depends on the constraints defined by the NPP's operating conditions. Some TES may also be well suited for integration with a particular type of advanced NPP but may not be the best suitable for NPPs in other categories, thus highlighting the importance of such category-specific classification rather than generalization. For example. Two-tank and thermocline thermal-oil systems ranked highly for low-temperature reactors but were found incompatible with medium- and high-temperature NPPs. It is recommended that either molten-salt sensible heat storage, solid based storage or latent heat storage systems be used for implementation with high-temperature advanced NPP systems. Latent heat storage systems ranked highly small-size reactor group (microreactors) across all temperature ranges. The potential flexibility of a two-tank molten-salt sensible heat storage system across all temperatures and sizes is readily apparent. Prior to beginning work on a new installation, this information could help developers better acquaint themselves with the storage technologies best suited for operating a particular type of advanced NPP.

Table 14. Summary of information gathered in this study to generate a few top-level technology recommendations for each NPP category.

	[redacted]			[redacted]			[redacted]		
Technology	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs	<25 MWth Microreactors	25-750 MWth SMRs/medium	>750 MWth Larger NPPs
[redacted]	15	16	16	15	16	16	13	14	14
[redacted]	13	13	13	9	9	9	9	9	9
[redacted]	11	12	12	11	12	12	9	10	10
[redacted]	10	11	11	7	8	8	7	8	8
[redacted]	8	9	9	8	9	9	8	9	9
[redacted]	6	6	6	6	6	6	6	6	6
[redacted]	6	6	5	5	5	4	5	5	4
[redacted]	14	14	14	14	14	14	12	12	12
[redacted]	13	14	14	13	14	14	12	13	13
[redacted]	10	10	9	9	9	8	9	9	8

Blue: Ranked highest; White: medium ranking; Red: Ranked lowest

In summary, this study lays out the preliminary steps for overcoming the research gaps that must be addressed in order to generate greater benefits when matching each TES technology with a particular advanced NPP category. In future work, results and findings from this study will be incorporated with the INL FORCE platform utilized for technoeconomic analysis of integrated energy systems.

6. ACKNOWLEDGEMENTS

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