CHAPTER FIVE

Selecting Favorable Energy Storage Technologies for Nuclear Power

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5.1 INTRODUCTION

In recent years, growth in electricity generation from variable renewable energy sources and inexpensive natural gas has been significant [1]. Market deregulation has led to an environment in which nuclear power plants that have traditionally operated at close to full capacity have been called upon to operate more flexibly and compete directly with newer plants [2]. Consequently, concerns have been raised that nuclear power plants will need to adapt to the new paradigm or risk being shuttered due to disadvantageous economics [3]. One proposed solution to this challenge is integrating energy storage, which could increase available revenue by enabling more flexible operation while reducing operational costs by stabilizing power output, which lowers maintenance expenses and improves safety by avoiding unnecessary thermal stresses from cycling [4,5]. However, the appropriate energy storage technology for enhancing the flexibility of a nuclear power plant is not immediately obvious and will depend on a variety of site-, plant- and market-specific factors. The compatibility of an energy storage solution can be measured across many metrics, including environmental impact, technical maturity, and cost.

Nuclear power plants (NPPs) provide the US electricity grid with a substantial fraction of total generation (approximately 20%) [6] and an even larger fraction of its low-carbon power (almost 60%) [7]. Traditional

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operation of NPPs provides the grid with stable electricity generation throughout the day while producing less greenhouse gas emissions over the life cycle of the plant than other electricity-generating units. On average, nuclear reactors produce 66 gCO_2e/kWh in life-cycle emissions, mostly from plant construction and fuel preparation (e.g., mining, enrichment, and fabrication), which is almost an order of magnitude less than natural gas combined-cycle turbines [8]. Despite these benefits, ambiguous national policies affecting the nuclear power industry, low marginal prices from natural gas and renewable sources, and large, multidecade capital investments required to replace or retrofit the nuclear fleet have resulted in a difficult economic climate for NPPs [9, 10]. Hence, electricity generation from nuclear reactors has not increased since the 1990s, while electricity generation from natural gas, wind, and solar has grown considerably, as shown in Fig. 5.1 [11].

NPPs have been built globally, but new NPPs in the United States were not constructed for 2 decades during the period of 1996–2016. There has been renewed investment in nuclear power in recent years: The first new reactor in the United States since 1996, Watts Bar 2, went online in October 2016, and two additional reactors are projected to begin operation by 2021.

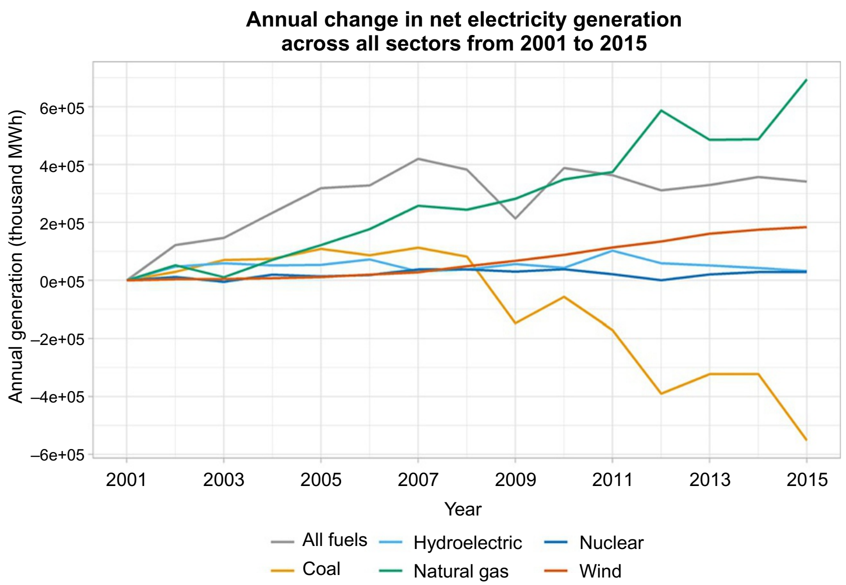

Fig. 5.1 Change in net electricity generation across all sectors from 2001 to 15 shows decreases in coal, increases in wind and natural gas, and stable output from hydro- and nuclear power plants [11].

The development of small modular reactors (SMRs) that might have less investment risk, introduction of direct policy support for NPPs, or a more aggressive policy stance toward reducing carbon emissions could foster a more favorable investment climate for NPPs [12]. The IAEA projects that nuclear power will continue to grow worldwide, with estimates of up to 42% growth by 2030 as electricity demand in Asia rises and nations attempt to meet their commitments under 2015's Paris Agreements. Though, expectations since the Fukushima disaster in 2011 have been more conservative due to price competition and stricter safety standards [13].

Continued reduction of carbon emissions from electricity generation in the United States will likely require multiple avenues of remediation [14]. While it might be possible [15], it is difficult and potentially cost-prohibitive for renewable energy sources to provide all of the carbon-free electricity generation in the United States due to resource variability and geographic dispersion [16]. Thus, it is worth investigating whether energy storage could supplement renewable electricity generation to help meet climate change mitigation goals by accommodating variability in renewable output while also improving the economic outlook for NPPs. Energy storage technologies could improve NPP performance by providing NPPs with multiple avenues for generating revenue, such as the delivery of ancillary services [17]. An integrated energy storage system could also bolster the resilience of NPPs against market trends by enhancing the flexibility of the plant, allowing operators to more easily ramp their supply of electricity to the grid to match changes in demand. Although the ramp rates of NPPs are typically constrained by economics or regulations rather than technical ability, the advantages of flexibility have been proved in the literature [18], and energy storage might provide plant operators a way to overcome these economic and regulatory barriers. Energy storage could also help reduce maintenance costs induced by thermal stresses from plant cycling [4,5]. In this chapter, several energy storage technologies are compared as potential candidates for near-term installation alongside newly constructed advanced nuclear power plants. Advanced NPPs are defined here as the Generation III + reactors currently being built in the United States, including the Westinghouse AP1000 and GE-Hitachi ABWR reactor designs [19].

Generation III + reactor designs, or *advanced NPPs* in this analysis, have many features that set them apart from previous generations. These reactors prioritize simpler systems that are intended to reduce capital costs and are also more fuel-efficient and safety-conscious. Other unique features of advanced NPPs include more standardized designs to simplify licensing, expectation for longer operating lives, higher availability due to a more robust design and some load-following capabilities, higher burnup, and the implementation of passive safety systems [19]. In this analysis, advanced NPPs were limited to commercial reactors >700 MWe in design, so SMRs were not considered. The Westinghouse AP1000 reactor was explored in greatest detail in this chapter due to its popularity in the United States. The AP1000 reactor was designed to ramp electricity generation by 5% of the plant's nameplate capacity per minute between 15% and 100% of the plant's maximum power output, but integrated energy storage could help further reduce operation and maintenance (O&M) costs and increase the plant's total output. The same principles for integrating energy storage with an advanced NPP apply to more traditional NPPs currently in operation [20].

Energy storage still faces many barriers to widespread adoption that need to be addressed, with different technologies in varying levels of development. Each technology's development timeline should be an important consideration when selecting compatible energy storage systems. Every storage technology considered for integration with an advanced NPP should also be assessed for its environmental impact [21]. Additionally, although energy storage technologies such as batteries are currently experiencing cost reductions, current market conditions indicate that costs still need to improve before they will be able to provide economic benefit to an advanced NPP [22]. For this reason, several thermal energy storage technologies were also considered in this chapter, since these energy storage systems can be 10–40 times less expensive than electricity storage [23]. In this chapter, energy storage characteristics were matched to the specifications of Vogtle 3 and 4, two reactors currently under construction in Waynesboro, Georgia, to identify the most favorable technologies for integration with this representative power plant. Nineteen different energy storage technologies are compared in this chapter, all of which are listed in Table 5.1.

5.2 DESCRIPTIONS OF THE CONSIDERED ENERGY STORAGE TECHNOLOGIES

The energy storage technologies discussed in this chapter are described in more detail here. Additional parameters describing the operation of these systems are recorded in Appendix A.

Table 5.1 The Storage Technologies Considered and Compared in This Chapter Represent a Comprehensive But Not Exhaustive List of Available Technologies

Type of Energy Storage	Energy Storage Technology
Mechanical	Pumped-storage hydropower
	Compressed-air energy storage
	Flywheels
Electric	Supercapacitors
	Superconducting magnetic energy storage
Electrochemical (conventional batteries)	Lithium-ion
	Sodium-sulfur
	Lead-acid
	Nickel-cadmium
Electrochemical (flow batteries)	Zinc-bromine
	Vanadium redox
Chemical	Hydrogen
Thermal (sensible heat)	Underground thermal energy storage
	Hot/cold water
	Solid media
Thermal (latent heat)	Thermochemicals
	Molten salts
	Liquid air
	Phase change materials

5.2.1 Mechanical Energy Storage

5.2.1.1 Pumped Storage Hydropower

Pumped-storage hydropower (PSH) is the most developed energy storage technology in the world today. The IEA estimates that PSH installations account for 99% of the energy storage capacity worldwide [24]. In the United States, the PSH fleet consists of 42 plants accounting for 21.6 GW of capacity, or 97% of the total utility-scale electricity storage in the United States at the end of 2015 [25]. The construction of new PSH facilities in the United States stalled in the mid-1980s due to environmental opposition and the changing needs of the grid, triggered by the transition to restructured electricity markets [26]. However, models built by the DOE have shown that there is potential for 35 GW of additional PSH facilities to be installed by 2050, which would more than double the current capacity in the United States [25]. PSH plants store energy by pumping water from a lower reservoir to a higher reservoir using electricity generated during off-peak periods. During peak demand periods, the water flows back down to the lower reservoir, generating electricity. PSH facilities can offer developers better ramp rates than natural gas power plants for increasing the flexibility of the grid. The environmental impacts of PSH facilities are significant, though, and specific geographic conditions must be available to make construction viable. The investment costs for PSH plants can also be prohibitive [26].

5.2.1.2 Compressed Air Energy Storage

Compressed-air energy storage (CAES) facilities have been commercially deployed, but are not nearly as widespread as PSH plants. Only two full-scale CAES systems are in operation in the world today: one in Germany and one in the United States [26]. Like PSH plants, specific geographic formations are typically required for CAES installations. A CAES system stores energy by using off-peak electricity to compress air and store it in a reservoir. Although large, steel, aboveground containers can be built to use as a reservoir for the compressed air, naturally occurring salt caverns often provide a more cost-effective alternative. The compressed air is heated, expanded, and released to a combustor in a gas turbine during peak demand periods to generate electricity. CAES plants offer quick ramp rates like PSH facilities, but the efficiency of the energy storage and conversion process is relatively low compared with other energy storage technologies. Likewise, CAES plants are slower to respond to disruptions in the grid than quick-response technologies like flywheels or batteries [27].

5.2.1.3 Flywheels

Flywheels store kinetic energy with a spinning rotor. Controls and a power conversion system are used to convert AC power delivered by the grid or an individual power plant into the rotational energy of the rotor. The energy is later released by applying resistance to the spinning rotor. Flywheels have very low energy capacities compared with PSH and CAES systems but can deliver much more power per mass. In modern flywheel systems, the spinning rotor is contained in a thick, steel vessel that protects the rotor and the motor-generator used to convert electric energy into mechanical energy and vice versa. This containment vessel also protects surrounding workers from injury in the event of a catastrophic failure. The rotor is also surrounded by a vacuum to minimize the frictional loss of energy as the rotor spins [24,26]. Flywheels offer many benefits to developers, since they are a durable, modular, and quick-responding technology. Flywheel energy storage systems are also highly efficient, and their scalability to grid-scale applications has been proved [27].

5.2.2 Electrical Energy Storage

5.2.2.1 Supercapacitors

Capacitors store energy by collecting positive and negative charge on two conductive plates opposite one another and separated by a dielectric material. An electric field forms between the two plates that can be used to quickly store and release electricity. Supercapacitors, which are also called electric double-layer capacitors, usually have an energy density hundreds of times greater than that of a conventional capacitor. Supercapacitors store energy between two high-surface-area electrodes separated by an ion-permeable membrane. An electrolyte solution is used to carry charge between the two electrodes. The large surface area of supercapacitor electrodes allows for higher energy density but has the drawback of lower power density compared with conventional capacitors [28,29]. Compared with electrochemical batteries, supercapacitors could be characterized as having high power densities and low energy densities [27]. Figs. C.1–C.5 in Appendix C provide information on the relative power and energy density performance of supercapacitors versus electrochemical batteries.

5.2.2.2 Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) systems store energy in a magnetic field. This magnetic field is generated by a DC current traveling through a superconducting coil. In a normal wire, as electric current passes through the wire, some energy is lost as heat due to electric resistance. However, in a SMES system, the wire is made from a superconducting material that has been cryogenically cooled below its critical temperature. As a result, electric current can pass through the wire with almost no resistance, allowing energy to be stored in a SMES system for a longer period of time. Common superconducting materials include mercury, vanadium, and niobium-titanium. The energy stored in an SMES system is discharged by connecting an AC power convertor to the conductive coil [30]. SMES systems are an extremely efficient storage technology, but they have very low energy densities and are still far from being economically viable [27].

5.2.3 Electrochemical Energy Storage (Conventional Batteries)

5.2.3.1 Lithium-Ion Batteries

In recent years, lithium-ion batteries have been used as the energy storage technology of choice for consumer products, electric vehicles, personal electronics, and many other applications in which the weight of the energy storage technology needs to be minimized. In the past couple of years, lithium-ion batteries have also dominated the market for stationary grid-scale energy storage applications [26]. In a lithium-ion battery cell, energy is stored by causing positively charged lithium ions to travel through a liquid electrolyte to the opposing electrode, while electrons are transferred through an external circuit. When the battery is discharging, lithium ions are transferred back to the original electrode allowing for a discharge of energy through the external circuit. Lithium has a high galvanic potential, giving lithium-ion batteries favorable energy storage characteristics. However, lithium is also highly reactive when exposed to oxygen or water and must be packaged carefully. The lifetime and costs for this technology are not as favorable as other energy storage technologies, but lithium-ion batteries offer superior energy density and specific energy characteristics when compared with other commercially available electrochemical storage options. Thus, lithium-ion batteries are still the storage technology of choice for many mobile devices [29].

5.2.3.2 Sodium-Sulfur Batteries

Proponents of sodium-sulfur (NaS) battery systems claim that this technology is the most economically feasible battery storage option available, though NaS battery systems are like other battery systems in many ways. This technology's defining characteristic is its long discharge period, which can exceed 6h. NaS batteries require careful maintenance due to their extreme operating conditions. In a NaS battery, molten sodium and sulfur act as the battery's two electrodes, with beta-alumina acting as the solid electrolyte. Sodium ions layered in aluminum oxide carry charge across the electrolyte. Therefore, the operating temperature of the battery must be kept between 300°C and 350°C. The sodium must also be prevented from coming into contact with water and combusting. The high operating temperatures coupled with the high reactivity of the component elements used in NaS batteries have led to the implementation of strict safety measures [26]. Despite the safety challenges, NaS batteries offer superior energy densities and show promise for use in applications that require short and powerful bursts of energy [30].

5.2.3.3 Lead-Acid Batteries

Lead-acid batteries were the first rechargeable electrochemical battery storage available. This storage technology was first developed in the mid-1800s and was soon adopted for commercial applications. In a lead-acid battery, the cathode is made of lead-dioxide, and the anode is made of metallic lead. The two electrodes are separated by an electrolyte of sulfuric acid. As the battery charges, the sulfuric acid reacts with the lead in the anode and cathode to produce lead sulfate. A reverse process occurs when the battery is discharging. The production and decomposition of this chemical produce short and powerful bursts of energy, enough to start a car, boat, or plane. However, the gradual crystallization and buildup of lead sulfate in the battery's core severely reduce the cycle life of these batteries. As a result, they are not an ideal technology for several energy management services [26,28–30]. Due to their low energy density, this technology also has a larger footprint than other batteries [27].

5.2.3.4 Nickel-Cadmium Batteries

Nickel-cadmium (NiCd) batteries are direct competitors with lead-acid batteries since these batteries offer similar technical characteristics but with superior cycling abilities and energy density. In a NiCd battery, nickel oxide hydroxide is used to make the cathode, and the anode is made from metallic cadmium. An aqueous alkali solution is used as the electrolyte between the two electrodes. NiCd batteries are currently widely used for portable electronics applications, like lead-acid and lithium-ion batteries. Despite their superior cycling characteristics and energy density, NiCd batteries have their drawbacks. The batteries are constructed from highly toxic materials and suffer from the "memory effect," which requires that the battery be fully recharged even after a partial discharge [28–30].

5.2.4 Electrochemical Energy Storage (Flow Batteries)

5.2.4.1 Zinc-Bromine Flow Batteries

Zinc-bromine (ZnBr) flow batteries can be categorized as hybrid flow batteries, which means that some of the energy is stored in the electrolyte and some of the energy is stored on the anode by plating it with zinc metal during charging. In a ZnBr battery, two aqueous electrolytes act as the electrodes of the battery and store charge. The electrolyte solutions contain the reactive components, zinc and bromine, and as these solutions flow through the battery's cells, reversible electrochemical reactions occur, and energy is either charged to the battery or discharged. When the battery is charging, elemental zinc attaches to the carbon-plastic electrodes connecting each cell in the battery to form the anode, and bromine forms at the cathode. Carbon plastic is used for the electrodes because of the highly corrosive nature of bromine. A selective membrane is included in the battery's design to separate the electrolytes while still allowing ion transfer to maintain charge neutrality [26,29,30]. Flow batteries have many advantages including long lifetimes, modularity, and almost no energy loss throughout the technology's storage duration. However, the design for these battery systems can be very complex, which can lead to increased costs and difficulties in development [27,28]. ZnBr flow batteries also feature lower efficiencies and stricter operating conditions than most other battery storage technologies [30].

5.2.4.2 Vanadium Redox Flow Batteries

In contrast to ZnBr flow batteries, vanadium redox batteries (VRBs) only store energy within the electrolyte of the battery. VRBs are the most mature type of flow battery available. They were first developed in the 1980s and now constitute over 20 MWh of installed storage capacity worldwide. VRBs are used mostly for small- and medium-scale applications, but their utility in responding to variable generation from renewable energy resources has already been demonstrated. VRBs store energy with vanadium redox couples that are kept in two separate electrolyte tanks. As the electrolyte flows through the battery during charging, vanadium ions accept electrons at the anode and deposit electrons at the cathode. The reactions run in the reverse direction when the battery is discharging. As with ZnBr flow batteries, a proton-exchange membrane is needed to allow charge to flow, while the electrolyte solutions are kept separate. A significant advantage of VRB systems is that the two electrolyte solutions are chemically identical, which makes the operation of the battery much simpler and less expensive [26,28–30]. However, VRBs still face technical challenges, including low electrolyte stability and solubility, which can lead to decreased energy densities. The operating costs for VRBs also remain too high for the technology to be economically viable [30].

5.2.5 Chemical Energy Storage

5.2.5.1 Hydrogen Energy Storage

The production of hydrogen for energy storage is different than many of the other technologies considered in this report. First, rather than simply charging an energy storage device directly, hydrogen must be produced from an alternative resource. Hydrogen can be produced through the electrolysis of water using electricity produced by a nearby power plant or another electricity-generating unit. An electrolyzer introduces an electric current to the water to produce hydrogen and oxygen [28,30]. Two primary electrolysis technologies are currently available, alkaline electrolysis and proton-exchange-membrane (PEM) electrolysis, and both operate at relatively low temperatures (<100°C). However, high-temperature hydrogen production methods (700–900°C) are being researched and could be more compatible with nuclear power plants [31]. After the hydrogen is produced, it must be stored or used for another application. Possible postproduction uses include power-to-power, when hydrogen is stored in an underground cavern or pressurized tank to be converted to electricity later using either a fuel cell or a hydrogen-fueled gas turbine. Other postproduction uses include power-to-gas, when hydrogen is either blended with natural gas or used to create synthetic methane; power-to-fuel, when the hydrogen is used as a fuel for the transportation sector; and finally power-to-feedstock, when produced hydrogen is used for chemical and refining industries [32]. Although hydrogen production is a versatile energy storage method, offering clean and efficient electricity generation as well as scalability and a compact design, many challenges still face this technology. The primary limitations of hydrogen energy storage systems are the durability of the system components, high investment costs, and possible geographic requirements related to the hydrogen storage vessel [28,30].

5.2.6 Thermal Energy Storage (Sensible Heat)

5.2.6.1 Underground Thermal Energy Storage

Underground thermal energy storage (UTES) systems store energy by pumping heat into an underground space. There are three typical underground locations in which thermal energy is stored: boreholes, aquifers, and caverns or pits. The storage medium typically used for this method of thermal energy storage is water. Boreholes are man-made vertical heat exchangers that work to transfer heat between the energy carrier and the ground layers. Conversely, aquifers and underground caverns or pits are natural storage spaces for thermal energy. In aquifers, thermal energy is transferred to the aquifer by injecting or extracting hot or cold water from the aquifer itself. Finally, thermal energy stored in underground caverns or pits is stored in a large underground reservoir. Although, this last form of underground thermal energy storage is technically feasible, installations have been limited due to high investment costs. Additionally, although UTES systems are a convenient form of bulk thermal energy storage, their success is largely dependent on surrounding geographic conditions and a local need for district heating. UTES systems are incapable of contributing to high-temperature applications since it is impractical to store water underground above its standard boiling temperature for typical operating pressures [24,33].

5.2.6.2 Hot/Cold Water Storage

Hot and cold water storage tanks are probably the most prominent form of thermal energy storage. These energy storage systems are used primarily to shift the energy demand for the heating and cooling of residential and commercial buildings to off-peak periods to reduce costs. There are many different versions of this technology. For example, domestic water heaters can be used as a distributed form of thermal energy storage. In France, the thermal energy storage capacity available in domestic electric water heaters is responsible for reducing the country's peak energy demand in the winter by about 5%. By allowing the utilities to gain control over individual water heaters throughout the country, the peak energy demand can be reduced, and costs are returned to the consumer [24]. Steam accumulators are another form of hot water energy storage in which steam produced by a power plant is stored directly as a pressurized saturated liquid [34]. In a typical thermal energy storage system using hot or cold water, the device chills or transfers heat to the water, which is then stored in an insulated tank. The water is held at temperatures either right above the freezing temperature of water or right below the boiling temperature. Pressurized storage tanks can hold water at even higher temperatures. Even still, the storage output temperature of this technology is severely limited [24,29].

5.2.6.3 Solid Media Storage

Water has a very high heat capacity, and as a result, water has a high energy storage density. However, as a form of sensible thermal energy storage, water also has limitations. Since the boiling and freezing temperatures for water are relatively close compared to other materials, such as concrete, water can only be heated to a certain temperature without causing it to boil, and it can only be cooled so much before it begins to freeze. Freezing or boiling water can have drawbacks because water is often transported as a liquid through pipes and stored in tanks or, in the case of UTES, underground caverns and aquifers. Solid media energy storage systems offer a form of sensible thermal energy storage for high-temperature applications. Common solid materials used for thermal energy storage include concrete, bricks, and rocks. These materials are inexpensive, environmentally friendly, and easy to handle. The energy density of solid materials is generally much lower than liquid storage media though [24,33]. Energy is usually transferred to a solid storage medium by first transferring the thermal energy to some heat transfer fluid that runs alongside the solid storage medium as in a conventional heat exchanger [35]. The solid storage medium could also be electrically heated, as with firebrick thermal energy storage systems [36].

5.2.7 Thermal Energy Storage (Latent Heat)

5.2.7.1 Thermochemicals

Thermochemical storage (TCS) systems have emerged as a potential energy storage solution recently due to the technology's superior energy density and absence of energy leakage throughout the technology's storage duration. TCS systems store energy in endothermic chemical reactions, and the energy can be retrieved at any time by facilitating the reverse, exothermic reaction. The storage output temperature is dependent on the properties of the thermochemical that was used as the storage medium [24]. Typically, thermochemical energy storage refers to two main processes, thermochemical reactions and sorption processes. Thermal adsorption reactions can be used to store heat or cold in the bonding of a substance to another solid or liquid. A common sorption process used in TCS systems is the adsorption of water vapor to silica gel or zeolites. During charging, the water is desorbed from the inner surface of the adsorbent and is adsorbed again when the stored energy is discharged from the system [33]. Alternatively, heat can be stored by directing thermal energy to an endothermic chemical reaction. In this reaction, a thermochemical absorbs the energy and splits into separate substances, which can be stored until the energy is needed again. The reverse reaction occurs when the two substances are recombined and thermal energy is released through this exothermic reaction. The latent heat of the reaction for the selected thermochemical is equal to the storage capacity of the system [37]. Although the energy densities of thermochemicals are greatly superior to other energy storage technologies, thermochemicals are currently economically infeasible [27].

5.2.7.2 Molten Salts

Molten salts are a phase change material that is commonly used for thermal energy storage. Molten salts are solid at room temperature and atmospheric pressure but change to a liquid when thermal energy is transferred to the storage medium. In most molten salt energy storage systems, the molten salt is maintained as a liquid throughout the energy storage process. Molten salts are typically made up of 60% sodium nitrate and 40% potassium nitrate, and the salts melt at approximately 220°C [29]. Molten salts are often used with concentrating solar power (CSP) plants to store thermal energy for electricity generation [24]. In CSP plants, excess heat that is not used for electricity generation is diverted to the molten salt, which is then stored in an insulated tank. After sunset, this thermal energy can be used to produce steam and generate electricity when the sun is no longer providing energy to the CSP plant. This thermal energy storage capacity can also be used to smooth electricity production throughout the day and mitigate the variability associated with solar PV technologies [38]. In fact, the integration of thermal energy storage capacity can increase the capacity factor of a CSP plant from 25% to nearly 70% [29].

5.2.7.3 Liquid Air

Liquid air energy storage (LAES) technologies are gaining traction as an efficient and cost-effective energy storage method due to their large scale and long duration as well as their compatibility with existing infrastructure. LAES systems store energy using a method similar to CAES systems. Instead of storing compressed air in a large cavern, though, the volume of the gas is reduced further by refrigerating the air and liquefying it. The liquid air is then stored in an insulated, low-pressure tank aboveground, eliminating the geographic requirements associated with CAES systems. In LAES systems, natural gas is typically burned to drive the expansion process. However, the advanced adiabatic and isothermal compression methods that are being developed for CAES systems are applicable to LAES systems as well. Utilizing waste heat or cold from other processes, such as LNG terminals or landfill gas engines, could further improve the efficiency of this technology and eliminate the need for an external energy source [39].

5.2.7.4 Phase Change Materials

Although sensible thermal energy storage can be effective and relatively inexpensive, latent thermal energy storage technologies offer superior energy densities and target-oriented discharge temperatures. Molten salts and liquid air are both specific types of phase change materials (PCMs) that have developed into independent technologies due to their technical maturity. In theory, any PCM can be used for thermal energy storage, but only a few have been proved as effective. With PCMs, as thermal energy is transferred to or away from the chosen storage medium, the material changes phase. Since all of the thermal energy transferred to the material is directed to changing the material's phase, PCMs absorb and release heat isothermally. Depending on the material used, PCM thermal energy storage systems can be used for either shifting daily energy time-of-use or seasonal energy storage. However, although these materials can store 5–14 times more thermal energy per unit volume than sensible energy storage technologies, a phase change material must have very specific properties to be an effective storage medium. For example, to be used as latent heat storage medium, PCMs should have a phase-transition temperature that aligns well with the desired operating temperature, a high latent heat of fusion, and a high thermal conductivity. These materials can also be expensive and rare, which could slow the technology's progression toward maturity [33,40].

5.3 COMPREHENSIVE COMPARISON OF ENERGY STORAGE TECHNOLOGIES

Several diverse data sets regarding energy storage performance characteristics were curated as part of this work (see Appendix A). The performance data and unique energy storage characteristics were categorized into five principal bins (described further below): technical maturity, economic feasibility, environmental impact, logistic constraints, and policy and market considerations.

5.3.1 Technical Maturity

The maturity of each energy storage technology was determined using a widely accepted assessment technique originally developed by NASA and DOD that has been tailored by the DOE for application to energy-related technologies. This framework is called the *technology readiness assessment* and is useful for assigning a *technology readiness level* (TRL) to a technology on a scale of 1–9 [41]. This framework is recorded in Table 5.2.

Each storage technology considered in this analysis was assigned a TRL score between 1 and 9 that corresponds to the technology's current stage in development, based on the methodology developed by the DOE. This score allows for easy comparison of energy storage technologies. Technical maturity is important for NPPs close to beginning operation or when considering retrofitting existing NPPs, but might not matter so much for NPPs early in their development timeline.

5.3.2 Economic Feasibility

Energy storage technologies often have widely varying energy and power costs. For example, one technology might have higher power-related costs (e.g., generation assets for pumped hydropower energy storage), while another technology could have higher energy-related costs (e.g.,

Table 5.2 DOE Technology Readiness Level Framework [41]

Relative Level of Technology Deployment	Technology Readiness Level	TRL Definition	Description
System operations	TRL 9	Actual system operated over the full range of operating conditions	Actual operation of the technology in its final form, under the full range of operating conditions
System commissioning	TRL 8	Actual system completed and qualified through test and demonstration	Technology has been proved to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development
	TRL 7	Full-scale, similar (prototypical) system demonstrated in a relevant environment	Prototype full-scale system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment
Technology demonstration	TRL 6	Engineering/ pilot-scale, similar (prototypical) system validation in a relevant environment	Representative engineering-scale model or prototype system, which is well beyond the lab scale tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness
Technology development	TRL 5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects
	TRL 4	Component and/ or system validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system

Table 5.2 DOE Technology Readiness Level Framework [41]—cont'd

Relative Level of Technology Deployment	Technology Readiness Level	TRL Definition	Description
Research to prove feasibility	TRL 3	Analytic and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytic studies and laboratory sale studies to physically validate the analytic predictions of separate elements of the technology
Basic technology research/ research to prove feasibility	TRL 2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions
Basic technology research	TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D)

supercapacitors) [22]. It can be difficult to directly compare the costs of different storage technologies for this reason. In this chapter, the full cost of installation was estimated for each energy storage option by calculating the cost of fulfilling a specific application's power and energy requirements. Since both per-kW and per-kWh capacity costs represent the full cost of investment for an energy storage system, the largest of these two *full costs* was estimated as representative of the investment cost for that technology. This allows for an objective comparison of energy storage technologies when considering energy storage integration for a specific NPP.

Alternatively, the costs of storage technologies could be compared by calculating a *levelized cost of storage* (LCOS) for each technology, although this method might not sufficiently address the differences between a technology's power and energy costs [42]. Using each technology's LCOS to compare costs might allow one's comparison to include other factors that affect economics, such as technology lifetime and storage degradation rate. However, a *full cost* comparison was used in this chapter, since the LCOS is a relatively new metric.

5.3.3 Environmental Impact

The greenhouse gas emissions produced by an energy storage system during operation are an example of one of the parameters contributing to a storage technology's environmental impact. Each technology's emissions were categorized as either nonexistent, present in insignificant amounts, or present in significant amounts. Each technology was then assigned a corresponding score of 0, 1, or 2 to represent their GHG emissions, which will help compare the environmental impact of several energy storage options. Since environmental impact can tend to be a more subjective characteristic, calculating an *environmental impact score* allows for a more objective comparison. This methodology has been demonstrated before [43]. The parameters used to index each technology's environmental impact are listed in Table 5.3.

Adding up an energy storage technology's score for each environmental impact parameter yields that technology's *environmental impact score*. For each of the parameters listed in Table 5.3, a higher score corresponds to the

Table 5.3 The Parameters in This Table Were Selected to Describe the Life-Cycle Environmental Impacts of an Energy Storage System and Were Assigned Based on Review of the Available Literature

Environmental Impact	Description
Land and water impact	The footprint of a technology affects the available space for natural flora and fauna. The water footprint of a technology can limit the amount of water available for other purposes. A storage technology's impact was measured to be insignificant, not very significant, somewhat significant, significant, or very significant (i.e., scale from 0 to 4)
Greenhouse gas emissions	The quantity of GHG emissions produced during standard operation. Measured to be absent, present in insignificant amounts, or present in significant amounts (i.e., scale from 0 to 2)
Use of hazardous materials	The use of corrosive or otherwise hazardous materials in an energy storage system's construction can damage the environment if not handled properly during operation and disposal. Measured to be absent, present and recyclable, or present and nonrecyclable (i.e., scale from 0 to 2)

Table 5.3 The Parameters in This Table Were Selected to Describe the Life-Cycle Environmental Impacts of an Energy Storage System and Were Assigned Based on Review of the Available Literature—cont'd

Environmental Impact	Description
Production of hazardous fumes	Dangerous fumes produced by an energy storage system during operation that can negatively affect local wildlife populations. Measured to be either absent or present (i.e., scale from 0 to 1)
Nonenvironmental safety concerns	Some storage technologies present a risk of explosion or other safety concerns (e.g., strong magnetic fields). An energy storage system was measured to have no, minimal, some, or several safety concerns (i.e., scale from 0 to 3)
Resource depletion	The rate at which a nonrenewable natural resource is being depleted to construct a technology. Measured to be insignificant, somewhat significant, or very significant (i.e., scale from 0 to 2)

energy storage system having a more deleterious effect on the environment. Once again, calculating a numerical score in this way helps us compare the energy storage options considered in this chapter more objectively. A more detailed calculation is shown in Appendix D.

5.3.4 Logistical Constraints

The NPP under consideration might have a limited amount of space available to build an energy storage system, which would favor technologies with higher energy densities. Similarly, if the natural formations needed to construct a pumped-storage hydropower (PSH) or compressed-air energy storage (CAES) facility are not available to a potential developer, then these technologies should not be considered as viable solutions. Energy storage technologies that are not compatible with the resources available to an NPP should be eliminated from consideration when selecting favorable solutions.

5.3.5 Regional Policy and Market Conditions

Although policy and market information should not affect the calculation of favorability scores for the considered energy storage systems, the policy and market conditions in the region an NPP is being installed are still important. Since this is a subjective metric, a state's policy stance toward energy storage was ascertained by searching the DOE Global Energy Storage Database for any policies in the state regarding energy storage [44]. Likewise, the regional market conditions were assessed by establishing a *market variability* metric. A market was found to have high variability if the variability of the state's electric grid was measured to be in the 66th percentile of the United States. Variability was evaluated by identifying the percentage of a state's electricity generation from wind and solar energy and comparing this value to the rest of the United States [11]. A market was characterized as having mild variability if its variability lay between the 33rd and 66th percentiles and low variability if it fell within the 33rd percentile. These data are recorded in Appendix B. These conditions would affect nearly all energy storage technologies equally for a given region but could inform an NPP developer's decision to integrate energy storage in the first place.

5.3.6 Application Compatibility

Another important point of comparison for energy storage technologies are the specific benefits the technology can provide to the grid as a source of revenue or increased efficiency for a nuclear power plant. A technology's ability to provide a particular service is dependent on the parameters laid out in Appendix A. As a result, the services offered by electric and thermal energy storage technologies are often different. The storage applications that were considered are defined below. Information was found at the following references [17,24,26,28,45].

- *Energy arbitrage*: Energy arbitrage refers to the process of storing energy when prices are low and selling stored energy when the price of energy is higher. Baseload generators can simulate a flexible output by using energy storage, allowing them to take advantage of changing prices for electricity.
- *Frequency regulation*: Frequency regulation is the practice of balancing momentary differences between generation and demand. This service is required by North American Electric Reliability Corporation (NERC) mandatory reliability standards in an effort to maintain the grid's frequency at 60 Hz. Frequency regulation is typically automated and occurs on a minute-by-minute basis. Energy storage can provide frequency regulation services by discharging when demand exceeds supply and charging when supply exceeds demand.
- *Load following*: While frequency regulation is required to balance momentary differences between the supply and demand of electricity, load following is required to match larger trends in supply and demand.

Load following is characterized as power output that changes every several minutes. As the load changes throughout the day, the generation of electricity must increase to match demand. However, since power is purchased hourly, load-following services are needed to follow the load between auctions.

- *Voltage support*: Grid operators must maintain stable voltage levels in the transmission and distribution system. However, reactance produced by electronic equipment connected to the grid threatens to cause unacceptable voltage fluctuations. Reactive power must be injected to the grid to offset these fluctuations. Residential PV systems are a growing source of reactance on the grid.
- *Spinning, nonspinning, and supplemental reserves*: Reserves are needed to supply power to the grid in case any part of the supply suddenly becomes unavailable. In the United States, 15%–20% of the normal electricity supply capacity is usually available in reserves at any time. However, the reserves that are available to the grid cannot all respond to an outage immediately. Spinning reserves are generators that are online, but not supplying power to the grid; spinning reserves can respond to an outage within 10 s to 10 min. Nonspinning reserves are generators that are offline but can respond within 10 min. Nonspinning reserves can also be power plants that are not operating at full capacity and can ramp up in response to an outage. Supplemental reserves are the slowest to respond and can come online within approximately 1 h, depending on the type of power plant. Energy storage technologies can often simulate spinning reserves due to quick-response times.
- *Black start capabilities*: Black start capabilities are needed to energize the grid when the grid collapses and all other reserve capacity fails to back up the grid. Black start capabilities can provide power to consumers and restart power plants without drawing power from the grid. Energy storage technologies are well suited to provide this service to the grid.
- *Variable supply resource integration*: Energy storage can be used to optimize the output from VRES to increase the value of the transmitted electricity. In particular, energy storage can provide two valuable services to renewable energy sources. Energy storage can be used for capacity firming or enabling the use of an intermittent supply as a constant power source. In this chapter, this parameter refers to an energy storage technology's ability to assist with the integration of VRES with the electric grid.

- *Process heat applications*: The heat from a nuclear power plant could be stored with a thermal energy storage technology and used to power an external process that requires heat. For example, energy storage technologies can be used in combined heat and power plants to temporally align the consumer demand for electricity and heat.
- *Seasonal storage*: Energy storage technologies can be used to store energy for long periods of time to compensate for seasonal changes in supply and demand. For example, a thermal energy storage technology can be used to store heat in the summer to be used in the winter when this resource becomes more necessary.

5.3.7 Favorability Analysis

Finally, to determine a technology's overall compatibility with a specific application, the environmental impact, technical maturity, and economic feasibility for each energy storage option should be compared. This could be done by adding up each of the discussed numerical scores (i.e., TRL, full cost or economic feasibility, and environmental impact) and weighting these scores according to the user's individual preferences. A similar methodology was employed in this chapter when comparing energy storage options, as shown below:

$$F = EI \cdot \overset{[0,1]}{W_1} + EF \cdot \overset{[0,1]}{W_2} + T \cdot \overset{[0,1]}{W_3} \tag{5.1}$$

where W represents the chosen weighting factors, EI is the environmental impact score, EF is the economic feasibility score, T is the technical maturity, and F represents the overall favorability score. The weighting factors in this equation allow the user to change the relative importance of each component score to match the individual characteristics of the NPP under consideration (by assigning a value between zero and one). Appendix D contains additional information regarding the calculation of the terms in Eq. (5.1) If a single commercial application is being analyzed, then the technologies can also be sorted by whether the storage technologies are fully compatible, somewhat compatible, or incompatible with the required service (these data are recorded in Appendix A). Thus, the technology with the highest favorability score that is also fully compatible with the required service would be recommended for the application under consideration.

However, in addition to the weighted sum in Eq. (5.1), some energy storage options should be eliminated from consideration due to several constraints. Budget constraints determine whether the cost of a technology option exceed the user's budget for installing an energy storage system. Additionally, logistic constraints consider whether a technology has sufficient space and has access to any required geographic features and whether a technology has sufficient mobility, if a mobile system is desired.

5.4 CASE STUDIES

Two case studies are discussed in detail to show how energy storage technologies might be compared for real-world applications.

5.4.1 Case Study #1: Pumped Storage Hydropower in France

France presents a unique scenario for energy storage and nuclear power due to the country's high concentration of electricity generation from nuclear power. Hydroelectric facilities in France serve an important secondary purpose by operating as an inexpensive and flexible form of energy storage. This energy storage capacity is critical since the start-up time of a typical nuclear reactor can be up to 40 h, while almost 15,000 MW of hydroelectric capacity can be brought online in a matter of minutes [46]. Although both run-of-river- and reservoir-type hydroelectric facilities can operate as energy storage systems, the type of hydroelectric facility considered in this analysis is pumped-storage hydropower. These facilities can be used to pump water to a higher elevation during periods of low demand so that this water can be used to generate additional electricity to meet peak load. PSH facilities make up approximately 16% of hydropower capacity in France, or around 4–5 GW. On a normal day, this energy storage capacity is used to provide about 4 h of additional generation during periods of high consumption, as displayed in Fig. 5.2 [46].

For this case study, it was assumed that an energy storage developer was hired to address the French government's concerns and provide additional flexibility for the nation's large nuclear power fleet. Table 5.4 provides parameters that constrain the case study for France. A timeline of 1–5 years was chosen because technical maturity is critical to this simulation, considering the actual energy storage deployment in France occurred decades ago.

To compare energy storage options for this case study, the weighting factors for technical maturity, economic feasibility, and environmental impact were set to 1, 0.8, and 0.5, respectively. Note that the selection of these weighting factors is mostly arbitrary and could be changed by another interested user. The resulting simple calculation yields the following energy

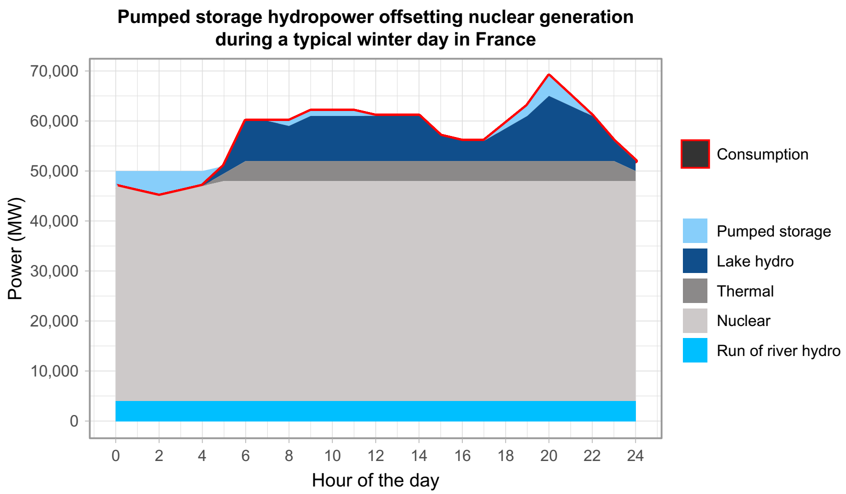

Fig. 5.2 France uses pumped-storage hydropower powered by nuclear during times of low demand to provide additional generation capacity at a later time to meet peak demand [46].

Table 5.4 Parameters Used to Describe the Situation of Using Energy Storage to Offset Electricity Generation From Nuclear Power in France

Parameter	Value
Required storage capacity	16 GWh
Required power	4 GW
Available budget	$40 million
Grid-scale service	Energy arbitrage
Timeline	1–5 years
Available geographic features	All

storage options in order of recommendation: (1) molten salts, (2) hot and cold water, (3) compressed-air energy storage (CAES), (4) lead-acid batteries, (5) sodium-sulfur batteries, and (6) PSH. The result of PSH being listed in sixth place is at odds with the fact that the French chose to install PSH as their primary source of energy storage.

Additional investigation is required to explain this discrepancy. The two thermal energy storage systems on this list (molten salts and heated water) can be removed from consideration, since thermal energy cannot be transported efficiently across large distances relative to the ability to transport electricity [47]. Lead-acid and sodium-sulfur batteries are potential solutions since electricity can be transported efficiently, but these technologies had not yet been developed for large-scale installations during the implementation of the French system. Even today, the largest battery installations are no larger than 400 MWh [44]. As a result, batteries would only have been feasible as a distributed solution, which mitigates the economies of scale that can be achieved with centralized facilities.

This leaves only CAES as a superior recommendation over PSH. However, CAES facilities have only been successfully deployed a handful of times and require unique geologic conditions [24]. It is unlikely that the French government would have considered CAES to be a viable option at the time. The remaining preferred technology is PSH, which was the energy storage system chosen by the French. This scenario demonstrates how it is difficult to recommend a clear-cut winner when comparing energy storage options, but this chapter intends to provide the information and decision-making framework to select a solution from a group of viable options.

5.4.2 Case Study #2: Advanced Nuclear Power Plant in the United States

To provide an accurate picture of how favorable energy storage technologies might be selected for an advanced NPP built in the United States, the specifications of a single reactor at the Vogtle 3 and 4 site in Waynesboro, GA, were considered, where two new reactor units are being built by Southern Company [48]. Each of these reactors will utilize a Generation III + reactor design, the Westinghouse AP1000, in compliance with the Nuclear Regulatory Commission's (NRC) stricter safety standards implemented in response to the Fukushima disaster [19]. Each reactor at this site has an electricity generation capacity of 1117 MW [48]. Ideally, the chosen energy storage system would be able to offset the entire generation capacity of the advanced NPP when electricity prices are low, but a facility of this size is unprecedented for most of the considered energy storage systems (e.g., batteries).

The Westinghouse AP1000 reactor is also capable of some load following, so the energy storage system is only needed to supplement the advanced NPP's flexibility and provide additional income. In particular, the AP1000 reactor is capable of load following for up to 90% of its fuel cycle with a ±5%/min ramp rate and a ±10%/min step load change. The AP1000 is designed to cycle its power level from 100% to 50% and back to 100% when load following. This reactor is also designed to perform this fast cycling without generating excessive waste water or generating severe axial xenon oscillations, which improves the reactor's recovery time after cycling (i.e., 20%

power step increase or decrease within 20 min) [20]. Therefore, the maximum power output of the energy storage system was set at 30 MW. This aligns well with existing energy storage units and the available PSH resources from nonpowered dams. As with the first case study, the energy storage capacity of the system was chosen by sizing the system to offset 4 h of electricity generated during a period of low demand.

According to the current construction schedule for Vogtle 3 and 4, the reactor units are expected to be deployed in 2021 and 2022, respectively. Therefore, the installation of an accompanying energy storage system was projected to occur 6–10 years from now to account for the storage technology's construction timeline. Due to the plant's location in Waynesboro, GA, the energy storage system should have no significant space or weight constraints, since there is sufficient open land nearby. However, the footprint of the energy storage facility was still limited to 1% of the advanced NPP's footprint, which is approximately 2000 acres, to keep the size of the chosen energy storage facility within reasonable limits [48]. The developer's available budget for an energy storage system was estimated to be 1 million dollars based on the size of the facility (~0.1% of the total budget). This is probably reasonable considering Southern Company's budget for Vogtle 3 and 4 of approximately 20 billion dollars [49]. This budget was large enough to fund most of the energy storage options considered in this work and meet the requirements of the case study as detailed in Table 5.5. In future investigations, a much larger budget might be justified if the economic value of an integrated energy storage system has been successfully demonstrated.

Table 5.5 Parameters Used to Describe a Potential Energy Storage System for Plant Vogtle, Units 3 and 4

Parameter	Value
Required storage capacity	120 MWh
Required power	30 MW
Available budget	$1 million
Timeline	6–10 years
Available geographic features	Underground aquifer, elevation change, water source
Grid-scale service	Energy arbitrage, frequency regulation, load following, spinning reserves, nonspinning reserves, voltage support

The compatibility of the energy storage options considered in this chapter with the geography of the area surrounding Waynesboro, GA, should also be evaluated. First, the location of Vogtle 3 and 4 does not appear to be compatible with CAES, due to the lack of geologic formations such as salt and rock caverns [50]. However, based on an assessment of nonpowered dams in the United States, it appears that there is potential for PSH development as an energy storage system [51]. A map displaying possible locations for further PSH development is displayed in Fig. 5.3. This map indicates that 1–30 MW of additional energy generation is available near Waynesboro, GA, which coincides with the chosen power output of the potential energy storage system.

Underground thermal energy systems (UTES) also have specific geographic requirements similar to CAES and PSH facilities. This technology makes use of existing underground aquifers or lakes, geothermal resources, or sufficiently large caverns to store thermal energy. Data were gathered from a variety of sources to determine the availability of these resources nearby Waynesboro, GA. First, according to a map acquired from the US

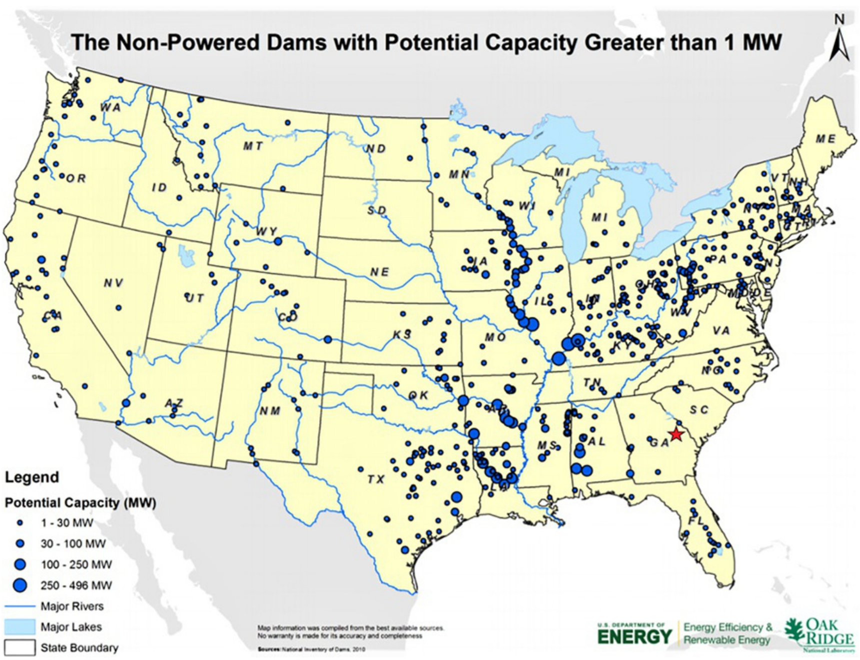

Fig. 5.3 Locations of nonpowered dams in the United States for potential new hydroelectric capacity [51].

Geological Survey, it appears that the southeastern coastal plain aquifer system runs relatively close to the sites of the Vogtle 3 and 4 reactors [52]. Therefore, for the sake of this simplified case study, UTES facilities were considered as viable energy storage options for Vogtle 3 and 4. Similar maps were obtained to assess the availability of geothermal resources and cave systems in the United States, but this information revealed that the geologic resources in the area are not adequate [53,54].

Table 5.5 summarizes the specifications that were used in this case study to simulate the requirements for energy storage integration with Vogtle 3 and 4. The grid-scale services listed in Table 5.5 correspond to the ancillary services that have been defined by Southern Company [55]. However, the results displayed in Fig. 5.4 are given in a *compatibility-agnostic* format. Since the application of an integrated energy storage system is highly dependent on the intentions of the developer installing the energy storage system, it is difficult to assume how energy storage will be used on the grid. The parameters displayed in Table 5.5 are specific to an energy storage system primarily used for shifting energy time-of-use, since it is likely that any integrated technology will perform this service to increase the flexibility and market power of the NPP.

The parameter values listed in Table 5.5 were altered to test an additional scenario focused on thermal energy storage (TES) technologies. With electric energy storage (EES) systems, it is simple to offset 4 h of energy generated during one part of the day by storing it and discharging the energy directly to the grid during a period of the day with more highly priced electricity. However, a TES system must be equipped with the means to generate electricity for the system to similarly discharge stored energy to the grid. Transferring 4 h of energy to another 4 h period could require the developer to install additional turbines at the power plant along with the additional infrastructure required to facilitate the steam cycle. Instead, the same 4 h of low-priced energy could be stored and then discharged over the remaining 20 h of the day to supplement the plant's output by a small amount. With TES, the advanced NPP could avoid selling electricity below its marginal costs, increase the amount of electricity sold to the grid, and minimize the amount of additional generation capacity needed. For this scenario, the required energy storage capacity remains the same, but the required power output was reduced to 6 MW.

Assume that the EES and TES system options described above are defined as Scenario A and Scenario B, respectively. The results for EES and TES systems were averaged to obtain each technology's overall

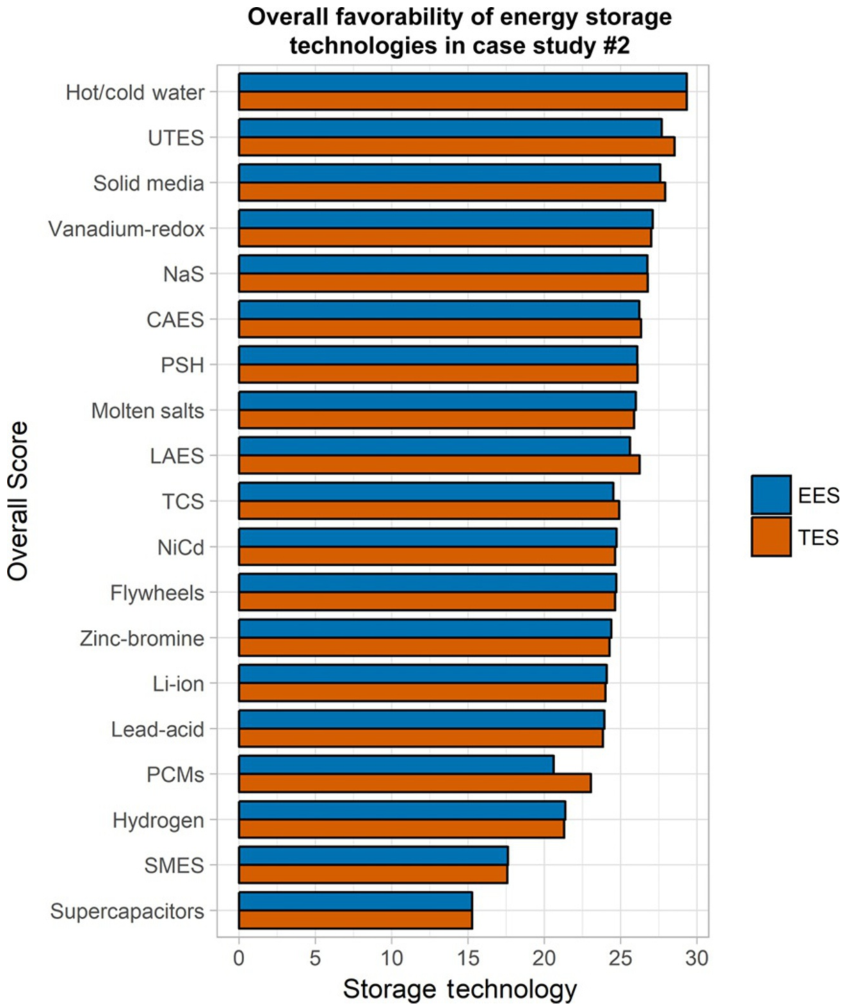

Fig. 5.4 Energy storage technologies ranked by overall favorability scores to reveal the most appropriate options.

favorability score. The energy storage technologies considered in this chapter were ranked according to these favorability scores, which were calculated using the parameters recorded in Table 5.5. Unlike Case Study #1, the environmental impact, technical maturity, and economic feasibility scores for each energy storage option were weighted equally in Case Study #2. Interestingly, there were only very slight differences between the two scenarios analyzing EES and TES systems for Case Study #2. In Scenario A (EES), PSH was ranked more favorably than liquid air energy storage (LAES), and CAES was favored over UTES, while in Scenario B (TES), the opposite was true. The averaged favorability scores for each energy storage option are displayed in Fig. 5.4. Note that in Fig. 5.4, the favorability scores have been reduced to a scale between 0 and 30. This could be done by dividing each score by the highest overall value and then multiplying each score by 30 to recalibrate. In this chart, phase change materials (PCMs) and superconducting magnetic energy storage (SMES) are represented by their respective acronyms.

5.5 CLOSING SUMMARY

This chapter describes several energy storage technologies compatible with NPPs and critically compares the characteristics of these energy storage options to determine the most promising technology for specific plants. This comparison includes analyzing the environmental impact, technical maturity, economic feasibility, logistic constraints, and policy and market considerations for specific grid-scale applications using a wide range of storage technologies. Two case studies were analyzed to illuminate a potential framework for objectively comparing technology options. While the scenario considered in Case Study #1 is useful for validation, Case Study #2 provides a more detailed view of which energy storage systems might hold the most potential for successful integration alongside a newly constructed advanced NPP. Since the storage technologies in Fig. 5.4 are ranked by their favorability scores with no consideration given to their compatibility with various grid-scale services, some filtering is still required before one might be able to identify the best technology for their application.

According to the results in Fig. 5.4, hot and cold water storage was identified as the most favorable energy storage system for the scenario presented in Case Study #2. Hot and cold water storage is a mature technology, although it has primarily been used for shifting thermal energy throughout the day for building heating and cooling. This technology is also inexpensive and has a minimal environmental impact; however, additional hardware, including extra turbines, might be required to convert the thermal energy into electricity if the NPP under consideration plans to continue operating at full capacity while the TES system is used for energy arbitrage.

A distinction can be made between the group of energy storage systems with favorability scores >25 and the rest of the considered technologies. In this more favorable group, we see a high concentration of thermal energy storage technologies and representation from both "bulk energy storage" technologies (CAES and PSH). This is most likely due to the low environmental impact and costs associated with these technologies. A couple of batteries, sodium-sulfur and vanadium redox, are also featured in the upper tier of technologies considered in Case Study #2. A few storage technologies that have seen widespread deployment in recent years, including lithium-ion batteries and flywheels, fall much lower on the list of preferred technologies for the case studies considered. Lithium-ion batteries and flywheels are uniquely suited for grid-level applications, like supplying frequency regulation and voltage support. When considering an energy storage system for installation alongside an NPP, however, these technologies are either too expensive for energy arbitrage or environmentally impactful compared with the other available options. The relatively low performance of lithium-ion batteries in Case Study #2 highlights the importance of identifying the specific needs of one's application to properly rank the available energy storage options.

Lithium-ion batteries, flywheels, and other similar EES technologies are also popular due to their compatibility with renewables. The quick charging and discharging characteristics and minimal geologic and environmental requirements offered by electrochemical batteries and flywheels match well with the intermittent nature of remote wind and solar energy. As a baseload generator, NPPs have different needs that might make energy storage solutions like PSH, CAES, and TES more suitable since they excel at storing large amounts of energy efficiently for a span of a few hours in the case of TES or several weeks with PSH and CAES. Vanadium redox and sodium-sulfur batteries also show effectiveness in long-term energy storage when compared with most other EES technologies. With additional commercial deployments of electrochemical batteries, the technical and economic competitiveness might improve to the point that lithium-ion batteries could be considered viable for complementing an NPP.

APPENDIX A: PERFORMANCE METRICS FOR THE CONSIDERED ENERGY STORAGE TECHNOLOGIES

These metrics were first recorded in *An Evaluation of Energy Storage Options for Nuclear Power* by Coleman et al. and are reproduced here. Further explanation for these metrics can be found in Coleman's manuscript [56].

1. Mechanical Energy Storage

Table A.1 Performance Metrics for Mechanical Energy Storage

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
PSH	500–8000 [30]	100–5000 [28]	5–100 [30]	2000–4000 [30]	6–10 h [30]
CAES	580 and 2860 [30]	110 and 290 [30]	2–120 [28]	500–1500 [24,30]	8–20 h [30]
Flywheels	0.0005–0.025 per unit, five total [26,57]	0.1–1.65 per unit, 20 total [26,57]	1000–5000 [30]	250–350 [30]	0–0.25 h [28]

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
PSH	Minutes [28]	Very small [30]	0.5–1.5 [30]	0.5–1.5 [30]	0.5–1.5 [30]
CAES	Seconds to minutes [28]	Small [30]	2–6 [30]	0.5–2 [30]	30–60 [30]
Flywheels	Seconds [28]	20% per h [30]	20–80 [30]	1000–2000 [30]	10–30 [30]

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
PSH	–	76%–85% [26]	10,000–30,000 [28]	50–60 [26]	∼3 [30]
CAES	–	∼70% [30]	8000–12,000 [28]	20–40 [28]	19–25 [30]
Flywheels	400–1500 [30]	90%–95% [28]	20,000–100,000 [26,28]	15–20 [26,28]	∼20 [30]

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
PSH	9 [26]	–
CAES	9 [26]	–
Flywheels	7 [26]	–

Table A.2 Environmental Impacts for Mechanical Energy Storage

Environmental Impact	PSH	CAES	Flywheels
Land and water impact	Very significant	Somewhat significant	Insignificant
Emissions produced during operation	Yes, but not very significant	Yes	None
Hazardous materials	None	None	None
Hazardous fumes	None	None	None
Short-term safety concerns	Some	Some	Some
Resource depletion	Insignificant	Insignificant	Insignificant
Geographic requirements	Yes	Yes	None

Table A.3 Compatible Applications for Mechanical Energy Storage

Service	PSH	CAES	Flywheels
Energy arbitrage	Compatible	Compatible	Incompatible
Frequency regulation	Somewhat compatible	Somewhat compatible	Compatible
Load following	Compatible	Compatible	Somewhat compatible
Voltage support	Incompatible	Incompatible	Compatible
Spinning reserves	Somewhat compatible	Somewhat compatible	Compatible
Nonspinning and supp reserves	Compatible	Compatible	Incompatible
Black start	Compatible	Compatible	Incompatible
VSR integration	Compatible	Compatible	Compatible
Seasonal storage	Compatible	Compatible	Incompatible
Process heat applications	Incompatible	Incompatible	Incompatible

2. Electrical Energy Storage

Table A.4 Performance Parameters for Electrical Energy Storage Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
Supercapacitors	0.0005 [30]	0–0.3 [28]	10,000 [58]	130–515 [24]	Milliseconds to 1 h [30]
SMES	0.001–0.015 [30]	0.1–10 [30]	1000–10,000 [28,30]	200–300 [30]	Milliseconds to seconds [30]

Continued

Table A.4 Performance Parameters for Electrical Energy Storage Systems—cont'd

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
Supercapacitors	Milliseconds, <1/4 cycle [28]	20%–40% [30]	0.01–1 [59]	200–10,000 [60]	2.5–15 [30]
SMES	Milliseconds, <1/4 cycle [28]	10%–15% [30]	0.2–2.5 [30]	1000–4000 [30]	0.5–5 [30]

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
Supercapacitors	500–5000 [30]	90%–95% [28]	100,000 + [28]	10–30 [30]	~6 [30]
SMES	500–2000 [30]	95%–98% [28]	100,000 + [28,30]	20–30 [28,30]	18.5 [30]

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
Supercapacitors	5 [24]	–
SMES	5 [24]	–

Table A.5 Environmental Impacts for Electrical Energy Storage Systems

Environmental Impact	Supercapacitors	SMES
Land and water impact	Insignificant	Insignificant
Emissions produced during operation	None	None
Hazardous materials	None	None
Hazardous fumes	None	None
Short-term safety concerns	Minimal	Several
Resource depletion	Somewhat significant	Somewhat significant
Geographic requirements	None	None

Table A.6 Compatible Applications for Electrical Energy Storage Systems

Service	Supercapacitors	SMES
Energy arbitrage	Incompatible	Incompatible
Frequency regulation	Compatible	Compatible
Load following	Compatible	Compatible
Voltage support	Compatible	Compatible

Table A.6 Compatible Applications for Electrical Energy Storage Systems—cont'd

Service	Supercapacitors	SMES
Spinning reserves	Somewhat compatible	Somewhat compatible
Nonspinning and supp reserves	Incompatible	Incompatible
Black start	Incompatible	Incompatible
VSR integration	Compatible	Incompatible
Seasonal storage	Incompatible	Incompatible
Process heat applications	Incompatible	Incompatible

3. Electrochemical Energy Storage—Conventional Batteries

Table A.7 Performance Parameters for Conventional Battery Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
Lithium-ion	0.25–25 [57]	0.005–50 [26]	600–2500 [30]	1200–4000 [30]	Minutes to hours [30]
NaS	~300 [57]	~50 [57]	300–500 [30]	1000–3000 [30]	Seconds to hours [30]
Lead-acid	0.001–40 [30]	~0–20 [28,30]	200–400 [30]	300–600 [28,30]	Seconds to hours [30]
NiCd	~6.75 [30]	~0–40 [28,30]	800–1500 [30]	500–1500 [30]	Seconds to hours [30]

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
Lithium-ion	Milliseconds, <1/4 cycle [30]	0.1%–0.3% [30]	200–500 [30]	30–300 [59]	75–200 [30]
NaS	Milliseconds, <1/4 cycle [28]	Almost zero [30]	150–250 [30]	140–180 [30]	150–240 [30]
Lead-acid	Milliseconds, <1/4 cycle [28]	0.1%–0.3% [30]	50–80 [30]	10–400 [30]	30–50 [30]
NiCd	Milliseconds, <1/4 cycle [28]	0.2%–0.6% [30]	60–150 [30]	80–600 [30]	50–75 [30]

Continued

Table A.7 Performance Parameters for Conventional Battery Systems—cont'd

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
Lithium-ion	750–1250 [61]	75%–90% [30]	~3000 at 80% DOD [30]	5–15 [28,30]	10 [62]
NaS	150–230 [30]	75%–90% [28,30]	2500–4500 [28,30]	10–15 [28,30]	80 [30]
Lead-acid	75–300 [30]	70%–80% [30]	500–1000 [28,30]	5–15 [28,30]	50 [30]
NiCd	150–300 [30]	60%–70% [30]	2000–2500 [28,30]	10–20 [28,30]	20 [30]

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
Lithium-ion	9 [63]	–
NaS	8 [26]	–
Lead-acid	9 [57]	–
NiCd	7 [30]	–

Table A.8 Environmental Impacts of Conventional Battery Systems

Environmental Impact	Lithium-Ion	NaS	Lead-Acid	NiCd
Land and water impact	Insignificant	Insignificant	Insignificant	Insignificant
Emissions produced during operation	None	None	None	None
Hazardous materials	Yes	Yes, recyclable	Yes, recyclable	Yes
Hazardous fumes	None	None	Yes	None
Short-term safety concerns	Several	Some	Several	None
Resource depletion	Somewhat significant	Somewhat significant	Very significant	Very significant
Geographic requirements	None	None	None	None

Table A.9 Compatible Applications for Conventional Battery Systems

Service	Lithium-Ion	NaS	Lead-Acid	NiCd
Energy arbitrage	Somewhat compatible	Compatible	Compatible	Somewhat compatible
Frequency regulation	Compatible	Compatible	Compatible	Incompatible
Load following	Somewhat compatible	Compatible	Somewhat compatible	Incompatible
Voltage support	Compatible	Compatible	Compatible	Incompatible
Spinning reserves	Somewhat compatible	Compatible	Compatible	Compatible
Nonspinning and supp reserves	Incompatible	Compatible	Somewhat compatible	Incompatible
Black start	Somewhat compatible	Compatible	Compatible	Compatible
VSR integration	Compatible	Compatible	Compatible	Incompatible
Seasonal storage	Incompatible	Incompatible	Incompatible	Incompatible
Process heat applications	Incompatible	Incompatible	Incompatible	Incompatible

4. Electrochemical Energy Storage—Flow Batteries

Table A.10 Performance Parameters for Flow Battery Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
ZnBr	~250 [57]	~50 [57]	150–1000 [30]	700–2500 [30]	Seconds to ~10 h [30]
VRB	~250 [57]	~50 [57]	150–1000 [30]	600–1500 [30]	Seconds to 24 + h [30]

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
ZnBr	Milliseconds, < 1/4 cycle [28]	Small, almost zero when electrolyte stored separately [30]	30–60 [30]	<25 [30]	30–50 [30]
VRB	Milliseconds, <1/4 cycle [28]	Small, almost zero when electrolyte stored separately [30]	25–35 [30]	<2 [30]	10–30 [30]

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
ZnBr	~100 [30]	65%–75% [30]	2000+ [28,30]	5–10 [28,30]	–
VRB	~166 [30]	65–75% [30]	12,000+ [28,30]	5–10 [28,30]	70 [30]

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
ZnBr	6 [26]	–
VRB	7 [26]	–

Table A.11 Environmental Impacts of Flow Battery Systems

Environmental Impact	ZnBr	VRB
Land and water impact	Insignificant	Insignificant
Emissions produced during operation	None	None
Hazardous materials	Yes, recyclable	Yes, recyclable
Hazardous fumes	None	None
Short-term safety concerns	Minimal	None
Resource depletion	Very significant	Somewhat significant
Geographic requirements	None	None

Table A.12 Compatible Applications for Flow Battery Systems

Service	ZnBr	VRB
Energy arbitrage	Somewhat compatible	Somewhat compatible
Frequency regulation	Compatible	Compatible
Load following	Compatible	Compatible
Voltage support	Compatible	Compatible
Spinning reserves	Compatible	Compatible
Nonspinning and supp reserves	Compatible	Compatible
Black start	Compatible	Compatible
VSR integration	Compatible	Compatible
Seasonal storage	Somewhat compatible	Somewhat compatible
Process heat applications	Incompatible	Incompatible

5. Chemical Energy Storage

Table A.13 Performance Parameters for Chemical Energy Storage Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
Hydrogen fuel cell	1000–1000,000 (underground cavern) [32]	0–50 [30]	15 [30]	1500–3000 [30]	Seconds to 24+ h [30]

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
Hydrogen fuel cell	Seconds, <1/4 cycle [28,30]	Almost zero [30]	500–3000 [30]	500+ [30]	800–10,000 [30]

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
Hydrogen fuel cell	500–800 [30]	20%–30% [32]	1000+ (fuel cell) [28,30]	5–15 [28, 30]	0.0019–0.0153 $/kW [30]

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
Hydrogen fuel cell	6 [29]	–

Table A.14 Environmental Impacts of Chemical Energy Storage Systems

Environmental Impact	Hydrogen
Land and water impact	Significant
Emissions produced during operation	None
Hazardous materials	Yes
Hazardous fumes	None
Short-term safety concerns	Some
Resource depletion	Insignificant
Geographic requirements	Yes

Table A.15 Compatible Applications for Chemical Energy Storage Systems

Service	Hydrogen
Energy arbitrage	Somewhat compatible
Frequency regulation	Incompatible
Load following	Somewhat compatible
Voltage support	Incompatible
Spinning reserves	Somewhat compatible
Nonspinning and supp reserves	Compatible
Black start	Somewhat compatible
VSR integration	Incompatible
Seasonal storage	Compatible
Process heat applications	Incompatible

6. Thermal Energy Storage—Sensible Heat

Table A.16 Performance Parameters for Sensible Thermal Energy Storage Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
UTES	~3900 [64]	–	~0.055 [64]	3400–4500 [24]	–
Hot and cold water (storage tanks)	10–2000 [24]	–	0.1–10 [33]	300–600 [24]	Minutes to hours [65]
Solid media (concrete)	>1100 [35]	–	~40 [35]	500–3000 [24]	~1 day [35]

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
UTES	–	Almost zero [33]	20–30 [65]	–	–
Hot and cold water (storage tanks)	Seconds to hours [65]	Almost zero [33]	20–30 [65]	–	–
Solid media (concrete)	–	–	~22 [35]	–	~5 [66]

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
UTES	–	50%–90% [24]	–	–	–
Hot and cold water (storage tanks)	–	50%–90% [24]	–	10–30+ [65]	–
Solid media (concrete)	–	50%–90% [24]	–	>2 [35]	–

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
UTES	8 [24]	< 250 [24]
Hot and cold water (storage tanks)	7 [24]	95–98 or 120–130 (pressurized) [24]
Solid media (concrete)	6 [35]	350 [35]

Table A.17 Environmental Impacts of Sensible Thermal Energy Storage Systems

Environmental Impact	UTES	Hot and Cold Water (Storage Tanks)	Solid Media (Concrete)
Land and water impact	Significant	Insignificant	Insignificant
Emissions produced during operation	None	None	None
Hazardous materials	None	None	None
Hazardous fumes	None	None	None
Short-term safety concerns	None	None	None
Resource depletion	Insignificant	Insignificant	Insignificant
Geographic requirements	Yes	None	None

Table A.18 Applications Compatible With Sensible Thermal Energy Storage Systems

Service	UTES	Hot and Cold Water (Storage Tanks)	Solid Media (Concrete)
Energy arbitrage	Incompatible	Compatible	Compatible
Frequency regulation	Incompatible	Incompatible	Incompatible
Load following	Incompatible	Incompatible	Incompatible
Voltage support	Incompatible	Incompatible	Incompatible

Continued

Table A.18 Applications Compatible With Sensible Thermal Energy Storage Systems—cont'd

Service	UTES	Hot and Cold Water (Storage Tanks)	Solid Media (Concrete)
Spinning reserves	Incompatible	Incompatible	Incompatible
Nonspinning and supp reserves	Incompatible	Compatible	Compatible
Black start	Incompatible	Incompatible	Incompatible
VSR integration	Incompatible	Compatible	Compatible
Seasonal storage	Compatible	Compatible	Incompatible
Process heat applications	Compatible	Compatible	Compatible

7. Thermal Energy Storage—Latent Heat

Table A.19 Performance Parameters for Latent Thermal Energy Storage Systems

Storage Technology	Energy Capacity (MWh)	Power Capacity (MW)	Energy Capacity Cost ($/kWh)	Power Capacity Cost ($/kW)	Discharge Time
TCS	–	–	8–100 [33]	1000–3000 [24]	1–24+ h [30]
Molten salts	~350 [38]	–	5–10 [66]	400–700 [24]	–
LAES	20–1000 [39]	–	260–530 [30]	900–1900 [30]	Several hours [30]
PCMs	–	–	10–50 [33]	6000–15,000 [33]	–

Storage Technology	Response Time	Storage Degradation Rate (%/Day)	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Specific Energy (Wh/kg)
TCS	–	Almost zero [30]	140–830 [37]	–	–
Molten salts	–	Very small [24]	170–420 [66]	–	80–190 [66]
LAES	Minutes [30]	<0.2% [39]	–	–	100–140 [39]
PCMs	–	Almost zero [33]	100 [33]	–	–

Table A.19 Performance Parameters for Latent Thermal Energy Storage Systems—cont'd

Storage Technology	Specific Power (W/kg)	Round-Trip Efficiency	Cycle Life (Cycles)	Technology Lifetime (Years)	O&M Costs ($/kW/Year)
TCS	–	80%–99% [24]	–	10–30+ [33]	–
Molten salts	–	40%–93% [24]	–	–	–
LAES	–	55%–80% [30]	–	25+ [30,39]	–
PCMs	–	75%–90% [33]	–	10–30+ [33]	–

Storage Technology	Technology Readiness Level	Storage Output Temperature (°C)
TCS	5 [24]	20–200 [37]
Molten salts	9 [38]	550 [29]
LAES	6 [39]	$<$400 [39]
PCMs	4 [40]	$-$40–400 [33]

Table A.20 Environmental Impacts of Latent Thermal Energy Storage Systems

Environmental Impact	TCS	Molten Salts	LAES	PCMs
Land and water impact	Insignificant	Insignificant	Insignificant	Insignificant
Emissions produced during operation	None	None	Yes	None
Hazardous materials	Yes	Yes	None	Yes
Hazardous fumes	None	Yes	None	None
Short-term safety concerns	None	Minimal	None	None
Resource depletion	Insignificant	Insignificant	Insignificant	Insignificant
Geographic requirements	None	None	None	None

Table A.21 Compatible Applications for Latent Thermal Energy Storage Systems

Service	TCS	Molten Salts	LAES	PCMs
Energy arbitrage	Compatible	Compatible	Compatible	Compatible
Frequency regulation	Incompatible	Incompatible	Incompatible	Incompatible
Load following	Incompatible	Somewhat compatible	Compatible	Incompatible
Voltage support	Incompatible	Incompatible	Incompatible	Incompatible
Spinning reserves	Incompatible	Compatible	Compatible	Incompatible
Nonspinning and supp reserves	Somewhat compatible	Compatible	Compatible	Somewhat compatible
Black start	Incompatible	Incompatible	Compatible	Incompatible
VSR integration	Compatible	Compatible	Compatible	Compatible
Seasonal storage	Compatible	Incompatible	Compatible	Compatible
Process heat applications	Incompatible	Compatible	Somewhat compatible	Compatible

APPENDIX B: POLICY AND MARKET CONDITIONS FOR ENERGY STORAGE TECHNOLOGIES

In this section, federal and state regulations affecting energy storage technologies are detailed. In the selection methodology discussed in this chapter, a region was said to have positive policy conditions if the state regulations at the plant site were supportive of energy storage. Federal regulations are listed in Table B.1, and state regulations are listed in Table B.2.

Table B.1 Federal Regulations Affecting Energy Storage Technologies

Regulation	Description	Impact
FERC Order 719	Requires ISOs and RTOs to allow demand response resources to participate in energy and ancillary service markets. Also requires shorter intervals for price calculations, which better accounts for variability and favors energy storage [67]	This order is favorable for energy storage technologies that primarily act as demand response resources
FERC Order 745	Requires that electricity markets pay demand response resources at the	This order had the same effect as FERC Order 719

Table B.1 Federal Regulations Affecting Energy Storage Technologies—cont'd

Regulation	Description	Impact
	market price for energy [67]	
FERC Order 755	The "pay-for-performance" order ensures that technologies providing regulation services are compensated according to the accuracy and speed of their response [67]	This order enables fast-responding energy storage technologies to receive more revenue for regulation than conventional generators
FERC Order 784	Expanded on the pay-for-performance order, FERC Order 755, by opening up ancillary services more broadly to energy storage participation [24]	This order further enhanced the profitability of energy storage and made the valuation of energy storage more transparent
FERC Order 890	Further opened up established energy markets to nongenerating resources such as demand response and energy storage [24]	Continued to create more markets for energy storage technologies to sell services
FERC Order 1000	This order requires public utility transmission providers to cooperate at a regional level. Neighboring regions must also coordinate to investigate all possible solutions to meet their requirements [68]	Regionally planned transmission and a clearer cost allocation process would open the market more to renewable energy developers, which could in turn drive the development of other emerging technologies
STORAGE Act of 2013	The Storage Technology for Renewable and Green Energy (STORAGE) Act of 2013 proposed a 30% ITC for businesses installing in-house energy storage systems and a 20% ITC for grid-connected	This policy would further enhance the economic viability of energy storage and encourage investors to pursue energy storage opportunities

Continued

Table B.1 Federal Regulations Affecting Energy Storage Technologies—cont'd

Regulation	Description	Impact
	installations [68]. This bill was not enacted	
H. R. 5350, Energy Storage for Grid Resilience and Modernization Act	H. R. 5350 would establish a 30% ITC for both businesses and individuals interested in either producing or installing energy storage technologies [69]. This bill is currently before the House Ways and Means Committee	If passed, this federal policy would greatly enhance the economic feasibility of many energy storage technologies

Table B.2 State Policies and Initiatives Affecting Energy Storage Technologies

State	Policy or Initiative	Description
California	CPUC SGIP rules	The CPUC's Self-Generation Incentive Program provides financial incentives for consumer storage projects [26,68]. The SGIP was conceived in 2001
	AB 2514	Assembly Bill 2514 passed by the California state legislature tasked the CPUC with exploring energy storage initiatives. In response, the CPUC established a procurement target of 1.325 GW of storage by 2020 for all investor-owned utilities [67]. This bill was passed in 2010
Colorado	Innovative Clean Technology program	This program was founded by Colorado to provide funding for energy storage research and development [67]. This program was founded in 2009
	Section 123 resources	This initiative established by state law provides funding for emerging technologies without requiring that the technology be economically competitive [67]. This initiative was established by state law in 2001
Hawaii	–	Hawaii electric companies included energy storage in their 2013 Integrated Resource Plan (IRP), and Maui is considering energy

Table B.2 State Policies and Initiatives Affecting Energy Storage Technologies—cont'd

State	Policy or Initiative	Description
		storage as an option for addressing wind curtailment [65]
New Jersey	Clean Energy program	This program has $2.5 million of state funding for energy storage projects. However, they must be connected to a renewable energy source and ideally would primarily provide resiliency services. Although, the state's *Energy Master Plan* concluded that energy storage was not currently economically viable and recommended against pursuing energy storage as a resiliency solution [65]
	Critical infrastructure program	This program has an additional $500 million for updating existing infrastructure that could be used to build energy storage installations to defer upgrading the transmission infrastructure [65]
New Mexico	Energy Storage Task Force	This task force was formed to investigate investment options in energy storage for the state [65]
New York	NY-BEST	The New York Battery and Energy Storage Technology (NY-BEST) consortium provides funding for energy storage development and is supported by the New York State Energy Research and Development Authority (NYSERDA) [65]
	Green Bank initiative	The state has pledged almost $1 billion in financing for energy storage and other "green energy" projects [65]
	Energy Highway	This initiative was proposed by the state for the purpose of incentivizing the process of updating aging infrastructure [65]. In 2013, the implementation of this proposal began
Oregon	–	Portland General Electric included energy storage in their 2013 RFP (request for proposals), opening the door for investment in energy storage installations [65]
Texas	SB 943	This bill required energy storage installations to be registered as generation assets when used to sell energy or ancillary services, limiting the

Continued

Table B.2 State Policies and Initiatives Affecting Energy Storage Technologies—cont'd

State	Policy or Initiative	Description
		benefits that energy storage can provide in the state [65]. This bill became law in 2011
	Texas Docket 39917	TD 39917 required energy storage charging and discharging to be considered wholesale energy transactions. This change improved the economics of energy storage and eliminated several market distortions in the location and operation of resources [67]. This initiative was issued in 2012
Washington	–	The Washington Utilities and Transportation Commission requested that utilities in the state include energy storage when considering resource options for their next IRP [65]
Other states	–	Connecticut, Maryland, and Maine are also evaluating energy storage and microgrid development as options to improve grid resiliency and enable smart grid technologies [65]

As described earlier in the chapter, regional market conditions were assessed by calculating the variability of electricity generation in each region. This was done by calculating the percentage of electricity generation from variable renewable resources in each NERC subregion. The results are displayed in Table B.3.

Table B.3 Market Variability in Certain Regions of the United States [70]

Region	Percentage of Wind and Solar Electricity Generation by Region
New England	3.58
Middle Atlantic	2.36
East North Central	3.90
West North Central	15.77
South Atlantic	0.63
East South Central	0.06
West South Central	8.66
Mountain	7.28
Pacific contiguous	12.63
Pacific noncontiguous	9.04

APPENDIX C: ENERGY STORAGE COST COMPARISONS

A large amount of data is contained in the tables shown previously in Appendix A, so these metrics are displayed graphically in the following figures for ease of comparison.

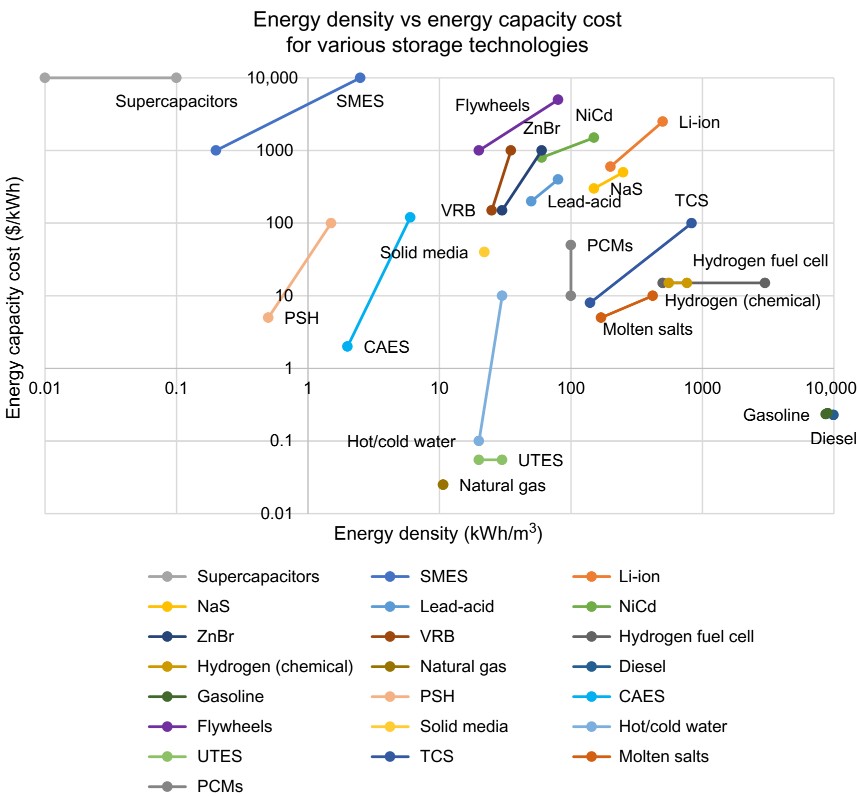

Fig. C.1 Comparing energy density and cost of storage for various technologies.

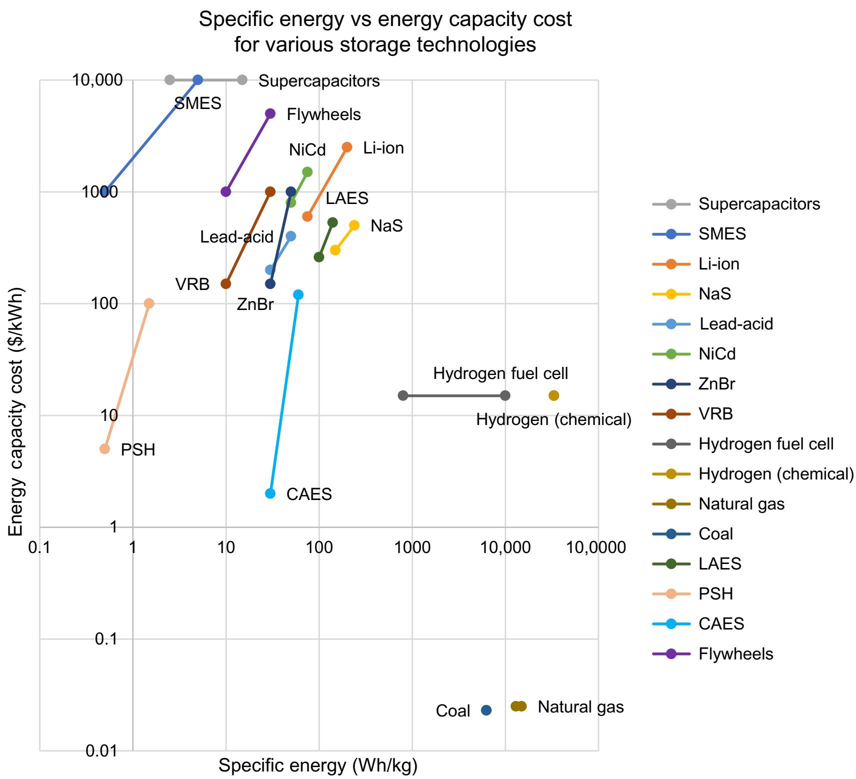

Fig. C.2 Comparing specific energy and cost of storage for various technologies.

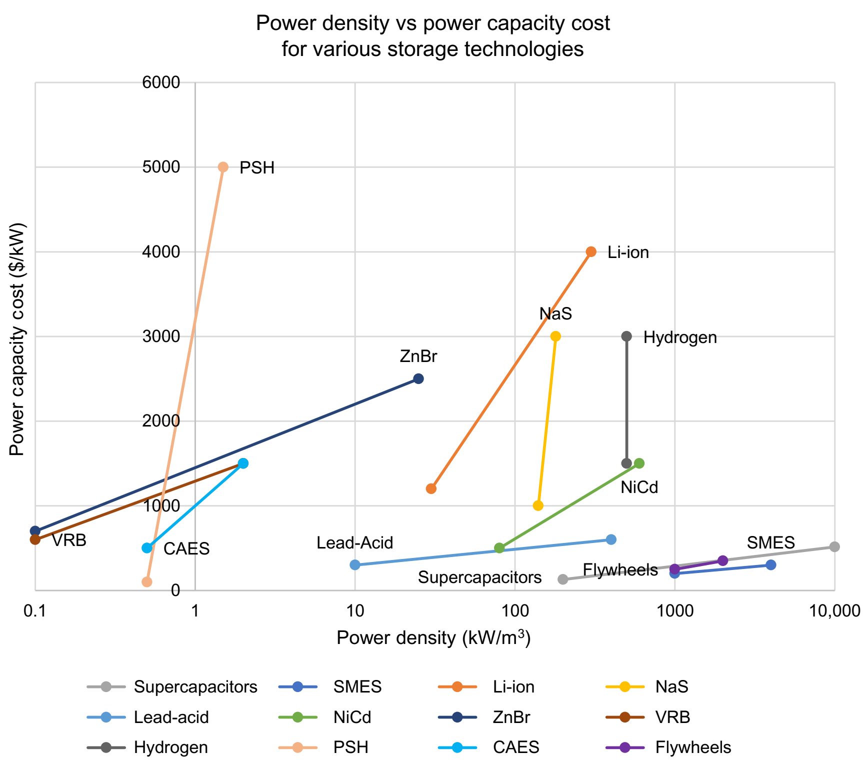

Fig. C.3 Comparing power density and cost of power for various technologies.

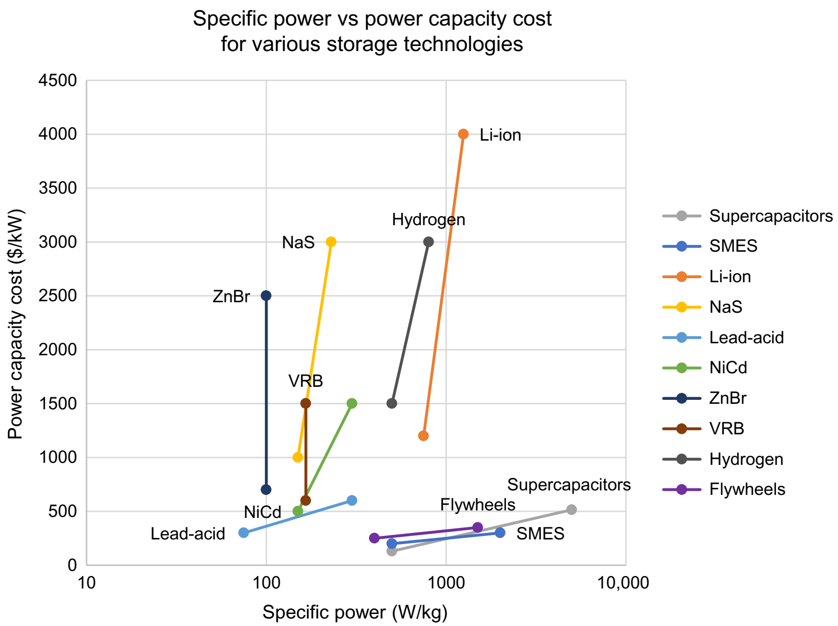

Fig. C.4 Comparing specific power and cost of power for various technologies.

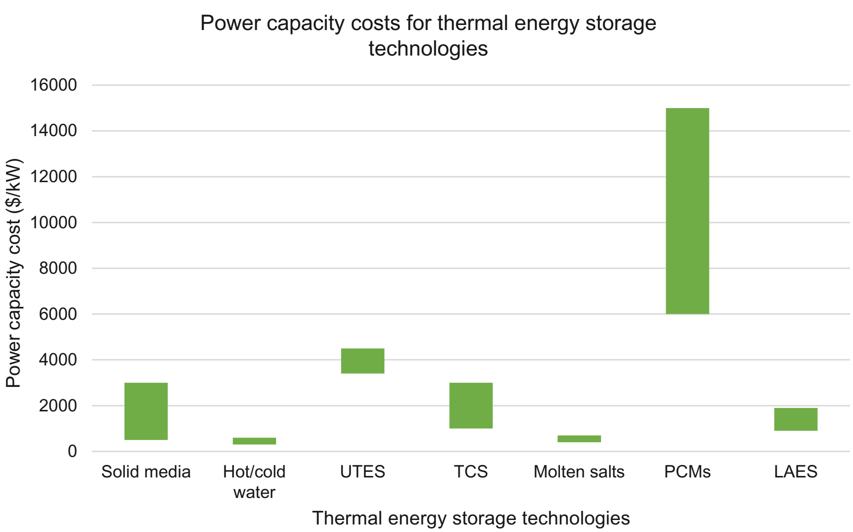

Fig. C.5 Comparing the cost of power for thermal energy storage technologies.

APPENDIX D: DETAILED SELECTION METHODOLOGY

A selection methodology for comparing energy storage technologies for integration with advanced NPPs was outlined generally in this chapter. More detailed equations for calculating "scores" for each of the selection criteria are included here.

Technical maturity: Starting from each technology's TRL score, a normalization function was used to calculate a score on a scale from 1 to 10. The technical maturity score is calculated as

$$T = \overset{[0,10]}{N}\overset{[0,9]}{(\mathrm{TRL})} \cdot \left(\frac{1 + \overset{[1,5]}{W} - 1}{5} \right) \Bigg|_{\max=10} \tag{D.1}$$

$$N(x) = \frac{x}{\max(x)} \times 10 \tag{D.2}$$

where T represents the technical maturity score, $N(x)$ represents the normalization function, TRL represents the technology readiness level, and W represents a weighting factor. This weighting factor is used to increase a storage technology's technical maturity by approximately one point for every 5 years between when the score is calculated and when the technology will be installed, which accounts for any future development.

Economic feasibility: The economic feasibility score is calculated by comparing the installed cost of an energy storage technology to an NPP's available budget. If the cost of the technology is greater than the NPP's budget, then the economic feasibility score will be zero. The least expensive energy storage option is given a score of 10, and the rest of the technologies are assigned a score between 0 and 10. The economic feasibility score is calculated as

$$\begin{aligned} IC &= \max\left(C_E \cdot E_{req},\, C_P \cdot P_{req}\right), \\ EF &= \begin{cases} 0, & \text{if } B - IC < 0 \\ \overset{[0,10]}{N}\left(\dfrac{B - IC}{B}\right), & \text{if } B - IC \geq 0 \end{cases} \end{aligned} \tag{D.3}$$

where P_{req} and E_{req} represent the NPP's power and energy requirements, C_P and C_E represent the energy storage system's power and energy capacity costs, IC represents the total installed cost for a storage technology, EF

represents a storage technology's economic feasibility score, and B represents the NPP's budget.

Environmental impact: First, some environmental impact parameters must be weighted. For example, if the energy storage technology will be installed at a safe distance from sensitive populations, the "use of hazardous materials" parameter should be weighted as less significant. This weighting is done using the factors shown in Table D.1.

Table D.1 Weighting Factors for the "Use of Hazardous Materials" Parameter

Proximity to Sensitive Populations (ft)	Weighting Factor
500+	0.2
300–400	0.4
200–300	0.6
100–200	0.8
0–100	1

The parameters in Table 5.3 are then normalized to a scale from 0 to 1 (using Eq. D.2) and averaged together. Once the parameter set has been averaged, the resulting value is set to a scale from 0 to 10 and subtracted from 10 so that a higher score represents a storage technology with a less significant environmental impact. This is the reverse of the scale used for the parameters listed in Table 5.3. The scale was inverted so that a higher score in this category would correlate to a more appropriate energy storage system, as is the case with the *technical maturity* and *economic feasibility* scores. A technology's overall environmental impact score is calculated as

$$EI = 10 - \overset{[0,\,10]}{N}\left(\sum\left[\frac{\overset{[0,\,1]}{W}\cdot\overset{[0,\,1]}{\varepsilon}}{6}\right]\right) \tag{D.4}$$

where EI represents the environmental impact score, N represents the normalization function, W represents a weighting factor, and ε represents the environmental impact parameters listed in Table 5.3.

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