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A Cost-Effective Future for Electricity Storage - An Examination of LCOS Studies on Stationary Applications

Jakob Phillip Klar

Technical University of Munich

Abstract

As the global energy transition gains momentum and the demand for electrical energy storage rises, decision-makers face the challenge to select the most suitable storage technology. This thesis presents a comprehensive techno-economic analysis of electrical energy storage technologies for stationary applications, focusing on the levelized cost of storage (LCOS) as a key metric for evaluating economic viability. Through a systematic review of several LCOS studies, the most cost-effective storage technologies were identified for various use cases. While the results show significant heterogeneity across studies, the findings still indicate that lithium-ion batteries and pumped hydro storage are generally the most viable and cost-effective technologies. However, unique considerations are observed for specific applications, such as flywheels for primary response. Future projections reveal that lithium-ion is most likely to dominate all applications except for seasonal storage, where hydrogen energy storage is expected to induce the lowest LCOS. The following pages provide valuable insights for decision-makers, policymakers, and industry stakeholders in selecting suitable and economically viable storage solutions. This thesis highlights the significance of storage technologies in supporting the global energy transition and emphasizes the importance of investment and rapid deployment to drive progress and achieve a sustainable energy future.

Keywords: cost-effectiveness; energy storage; energy transition; levelized cost of storage (LCOS); storage technologies

1. Introduction

It is a sunny summer day, and the entire country is powered by clean and sustainable renewable energy sources (RES). Suddenly, a storm hits. Windmills have to be shut down and clouds cover the sun, reducing the amount of electricity generated by photovoltaic (PV) systems. At the same time, factories keep operating and people continue to run their air conditioners and turn on the stove to cook dinner. Given the fluctuating character of renewable energy, how can we prevent blackouts and ensure a reliable and continuous electricity supply? The answer lies in effective energy storage (Behabtu et al., 2020, p. 1). Through storing excess energy during periods of high generation and unleashing it when needed, it represents an essential link, connecting renewable energy generation and consistent power availability. In today's context, as we face significant global challenges such as climate change, we urgently need to transition to clean energy systems. Electrical energy storage (EES) is a central pillar for achieving this. It unlocks the full potential of RES and enables their integration into the existing grid infrastructure (He et al., 2021, p. 1). However, this raises the question of which storage technology to choose.

Selecting the optimal energy storage technology for a given application is complex due to the diversity of the technologies and varying application requirements. To address this challenge, numerous studies have identified the Levelized Cost of Storage (LCOS) as a key metric for evaluating the economic viability of different storage technologies (Xu et al., 2022, p. 2). By estimating the cost of each unit of discharged energy, it promises to increase the compara-

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bility among technologies for a given application, thereby facilitating the selection of the most cost-effective EES option. However, methodological discrepancies and varying assumptions across these LCOS studies have led to divergent and sometimes conflicting results (Schmidt et al., 2019a, pp. 81-82). Consequently, reading different studies can lead to confusion rather than enlightenment, preventing stakeholders from making informed choices.

To mitigate this problem, this thesis aims to identify the most cost-effective EES technologies for various applications. Using a systematic review, it analyzes and compares different LCOS studies to reveal patterns and highlight differences in methodologies and recommendations. This provides valuable insights for decision-makers in determining the most appropriate EES technology for a specific application. The systematic review approach thereby reduces the risk of potential bias and strengthens the reliability of results. The pressing need to address climate change and the transition to renewable energy (International Renewable Energy Agency [IRENA], 2022) underscores the relevance of this research. EES technologies play a central role in successfully integrating RES into the grid and reducing carbon emissions (Aneke & Wang, 2016, pp. 350-351). This further increases the importance of choosing the most appropriate technologies. As climate change and the resulting energy transition are global issues, this thesis aims to provide a general view that can be applied universally. Therefore, it does not focus on specific countries or regions. This thesis ultimately contributes to a more resilient and sustainable future by reducing confusion and facilitating the selection of EES technologies.

The structure of this thesis is organized as follows. Chapter 2 lays the theoretical foundation, providing essential knowledge to understand the subsequent analysis of LCOS studies. This chapter presents the leading applications of EES (Section 2.1), explains the basic operating principles and characteristics of established EES technologies (Section 2.2), and introduces the concept of LCOS (Section 2.3). The analytical part of this thesis is included in Chapter 3. It starts with a detailed description of the overall methodology employed in this thesis, presented in Section 3.1. This section provides a comprehensive outline of the specific approach used to examine and compare diverse LCOS studies, encompassing data sources, selection criteria, and analytical frameworks. Next, Section 3.2 covers the key findings derived from reviewing and comparing these LCOS studies. These results are presented and visualized to highlight underlying trends and patterns. This forms the basis for the subsequent discussion in Section 3.3, where the results are critically examined, interpreted, and contextualized to identify underlying implications and draw conclusions. Building on this discussion, this section answers the central research question of this thesis by identifying the most cost-effective EES technologies for each application. Finally, Chapter 4 summarizes the main conclusions drawn from the analysis and highlights the essential findings and implications for technology selection. In addition, an outlook into the future is provided, exploring potential avenues for further research and development in the field of EES.

2. Theoretical Foundation

As described above, this chapter lays the theoretical foundation to understand the following analysis and comparison of LCOS studies. It utilizes several technical terms and concepts, such as power, discharge duration, or redox reactions. While many of these are widely known, some may be unfamiliar and are therefore defined in Appendix A.

2.1. Applications of Electrical Energy Storage (EES)

One of the critical challenges in maintaining a functional energy grid is ensuring a balance between power supply and demand. The voltage and frequency of the grid are very sensitive to power imbalances. As a result, a mismatch between supply and demand can cause deviations from their expected levels, resulting in power outages. This threatens the stability and reliability of the entire grid. Without the ability to store electricity, the power generated would have to equal the power drawn from the grid. The global energy transition further exacerbates this challenge, as the generation capacity of RES is often dependent on uncontrollable factors like weather conditions. Therefore, EES is essential to enhance the reliability of the grid. It can be used in several ways to overcome this and other problems (Hoff, 2022, p. 26). While EES is employed in diverse contexts, such as powering electric vehicles (EVs), this thesis focuses solely on large-scale[1] stationary applications, such as frequency response services or seasonal storage, as they play a crucial role in achieving the transition to a carbon-free grid (Soloveichik, 2011, p. 504). Moreover, off-grid applications and hybrid systems, such as batteries combined with PV, are beyond the scope of this thesis.

2.1.1. Frequency Control

Today, most of the world's electricity grids rely on alternating current (AC). As a result, most electrical equipment and appliances operate only when the voltage is supplied at a fixed frequency of 50 or 60 Hz (Hoff, 2022, p. 53). Frequency control aims to maintain the grid's stability by keeping its frequency within an acceptable range, usually a narrow corridor of less than 1 Hz (Greenwood et al., 2017, pp. 115-116).

Conventional power grids are characterized by having many rotating masses, such as turbines and generator rotors, which spin at synchronized frequencies. The kinetic energy stored in these masses (inertia) can uphold the synchronization of all generators for a few seconds, thus compensating for minor frequency disturbances. Today, the increasing decarbonization of the grid is leading to a growing share of inertialess power generators, like PV, which reduce the grid's self-stabilizing capability. This presents a challenge that can be

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[1] In this thesis, "large-scale" refers to applications with mean power ratings of 1 MW or more.

addressed by applying EES technologies (Hoff, 2022, pp. 26-31; Long Duration Energy Storage Council [LDES Council], 2021, p. 20). To be suitable for this inertial support application, EES technologies must respond quickly to grid fluctuations (Hoff, 2022, pp. 30–31). While inertial support can stabilize minor disturbances over short periods, more extensive disruptions, such as the collapse of central power plants, require other services known as frequency response. EES technologies demonstrate superior performance in delivering these services (Hoff, 2022, p. 32).

Frequency response assets are classified as primary, secondary, and tertiary reserves based on reaction speed (Hoff, 2022, pp. 31–36). Primary response covers the first seconds or minutes after a sudden frequency and voltage change occurs in the grid. The storage technologies must respond within milliseconds, providing or storing power until secondary response takes over (Hoff, 2022, pp. 35–36). Technologies used in secondary response take a few seconds to start up. Their job is to smooth out imbalances between demanded and supplied power for several minutes. In some countries, such as the UK, a new service called Enhanced Frequency Response (EFR) has been introduced, consolidating the functions of primary and secondary response (Greenwood et al., 2017, p. 117). Tertiary response shares similarities with secondary response but operates with longer reaction times in the order of minutes. It must sustain continuous service for extended periods, reaching up to several hours (Hoff, 2022, p. 35–36). Frequency containment reserve and frequency restoration reserve are other similar concepts to secondary and tertiary response (Ralon et al., 2017, p. 46). As the adoption of RES increases, the importance of frequency control becomes more pronounced. The inherent variability of energy supplied by RES can introduce imbalances in the grid's frequency, highlighting the need for effective frequency control mechanisms.

2.1.2. Power Quality

Power quality is similar to frequency control services. However, instead of focusing on maintaining a stable frequency on the grid, the goal here is to maintain the quality of the voltage and current waveforms. This includes smoothing out voltage fluctuations (flicker), harmonics, or notches. In addition, power quality also ensures a stable amplitude of the wave by counteracting disturbances, such as sudden voltage dips or swells, as well as overvoltage and undervoltage (Tesařová, 2011, p. 96, 98). Again, the increasing use of fluctuating RES reduces the power quality in the grid. EES can be used to effectively address these disturbances (Das et al., 2018, pp. 1213, 1223). Power quality services require a quick response time from EES technologies, often with storage durations of less than one minute (Behabtu et al., 2020, p. 3). Overall, response time is the most critical factor determining EES technologies' technical suitability for short-term storage services such as frequency control or power quality (Aneke & Wang, 2016, p. 365).

2.1.3. Time Shifting

As the name suggests, the basic idea of time shifting is to store energy and use it in later periods. In this respect, any use case of EES technologies could be assigned to this category (Hoff, 2022, p. 40). However, specific applications are centered around this idea. Energy arbitrage is a notable example. EES technologies used in this application do not need to respond rapidly. The goal is to purchase cheaply and store energy during off-peak times to sell it later during high-price periods, typically after a few hours of storage (He et al., 2021, pp. 8, 13). Thus, energy arbitrage helps offset the increased risk of price volatility associated with the energy transition (Long Duration Energy Storage Council, 2022, pp. 3–4).

The energy produced by generation technologies cannot always match the demand on the grid. This is especially true for RES technologies. RES energy supply relies on external and uncontrollable factors such as weather conditions and time of day. For instance, while electricity demand tends to rise in the evening when everyone comes home, RES generation, such as PV, declines during nighttime. Therefore, EES plays a critical role in storing excess electricity during periods of surplus and supplying it during times of decreased energy generation, enabling the balancing of daily fluctuations in electricity demand. This strategy is known as energy shifting (Hoff, 2022, pp. 40–42).

2.1.4. Peak Shaving

One problem that utilities and consumers face is that the peak demand for electricity is typically much higher than the average demand. This necessitates oversized power plants and infrastructure, which are only needed during rare peak times. (Hoff, 2022, p. 42) Peak shaving addresses this issue by reducing demand peaks and redistributing the load to later periods, narrowing the gap between maximum and average demand (Viernstein & Witzmann, 2020, p. 4). Using EES technologies, utilities can defer the need for further transmission and distribution (T&D) network expansions, commonly referred to as T&D investment deferral. Charging these technologies during off-peak hours to store electricity that can be released during peak demand reduces the required infrastructure capacity, minimizing the need for significant grid investments (He et al., 2021, p. 9; Ralon et al., 2017, pp. 10–11). Another way utilities try to reduce the need for overcapacity in power plants and infrastructure is by charging their customers extra fees if their demand for electricity is too high at any given time. EES technologies help customers to mitigate their peak power demand, resulting in cost savings by preventing these demand charges (demand charge management) (Hoff, 2022, p. 43–45).

2.1.5. Resiliency

ESS technologies can improve a grid's reaction to unanticipated events (resiliency) (Hoff, 2022, p. 47). There are several specific applications to achieve this objective. Providing backup power is one of them: Many electricity generation technologies require external energy to start up. This can be problematic during a blackout, as the generators cannot restart by drawing power from the grid. EES technologies can offer a solution by supplying power to restart generators (black start). In addition, they can provide emergency backup power or uninterruptible power supply (UPS) for critical equipment and infrastructure, such as servers or hospitals (Hoff, 2022, pp. 47–48, 153).

Even without a total blackout, events always cause disruptions in power generation. EES technologies ensure a reliable power supply by balancing the difference between demanded and generated electricity. The term power reliability summarizes services that achieve this (Schmidt et al., 2019b, Table S1). Nowadays, they are even more vital due to the variable nature of RES technologies. Wind turbines or PVs heavily rely on weather conditions. In extreme weather, windmills may have to be shut down, and clouds may cover the sun, preventing PV from creating enough electricity to meet the power demand. EES can mitigate this problem by providing power for hours or even days during severe weather conditions. Given the expected increase in unusual and extreme weather events due to climate change, the importance of long-duration EES as a critical enabler of power reliability will continue to grow (Long Duration Energy Storage Council, 2022, pp. 22–23).

2.1.6. Seasonal Storage

Seasonal storage is similar to time shifting, but the storage duration can be several weeks or months. This approach aims to smooth out seasonal differences in power generation capacity, such as the variation between solar energy in summer and winter. Additionally, annual peaks in demand, such as vacation periods, can be met without overbuilding the grid (He et al., 2021, pp. 8-9). Again, the energy transition further emphasizes the need for seasonal storage. For instance, the reduced power supply from photovoltaic systems in winter can be supported by long-term energy storage, which can be recharged during periods of high power generation in summer. EES technologies for this application share similarities with those employed for time shifting services. However, the discharge durations must be much longer, so a higher energy capacity is required. Self-discharge becomes crucial in seasonal storage as it accumulates over long storage durations and should therefore be as low as possible (de Barros Gallo et al., 2016, p. 815).

In conclusion, this section highlights the diverse range of stationary applications for EES technologies, each with its specific technical requirements. Understanding the operating principles and resulting characteristics of different EES technologies is essential to determine their suitability for particular applications. Thus, the subsequent section will provide an overview of the most significant EES technologies.

2.2. EES Technologies

Storing electricity poses a significant challenge since electrical energy cannot be readily stored but first must be converted into another form of energy. It can then be converted back to electrical energy later in time (Aneke & Wang, 2016, p. 355). EES technologies do just that. Generally, they can be classified as mechanical, electro-chemical, electrical, chemical, and thermal storage technologies based on the form of energy the electricity transforms into (de Barros Gallo et al., 2016, p. 800).

This thesis focuses on standalone technologies that use electricity as both the input and output form of energy (Power-to-Power) (Schill, 2020, p. 2059). In addition, this thesis relies on the availability of LCOS studies on the compared storage technologies. Therefore, the focus will be on more mature technologies with real large-scale applications. Thermal storage technologies are primarily used in hybrid systems to support other storage or generation technologies. In addition, the stored energy is often released in the form of thermal energy, for example, for heating purposes. While some Power-to-Power storage solutions exist, they are still in relatively early stages of development (Hoff, 2022, p. 137). Consequently, thermal energy storage is not included in this thesis. Similarly, electrical storage technologies are not analyzed. Supercapacitors and superconducting magnetic energy storage, the two most popular technologies in this category, are still rather immature (Das et al., 2018, p. 1209; de Barros Gallo et al., 2016, p. 816) and have limited LCOS studies available.

2.2.1. Mechanical Storage Technologies

Mechanical storage is one of the most popular and common ways to store electricity. Here, electrical energy is converted into potential or kinetic energy, which is then used to regenerate electricity later in time (Hoff, 2022, p. 55). Pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES) are the most popular and mature examples of mechanical storage. These three technologies will be further explained in the following.

PHS is by far the most widely used storage technology, making up around 95% of global EES deployments (Hoff, 2022, p. 97). It stores electricity by pumping water or another liquid from one reservoir to another higher reservoir. When electricity is needed, the process is reversed, and the potential energy of the water drives turbines to generate power (Hoff, 2022, p. 77). While PHS historically mainly used rivers to create water reservoirs, nowadays, the focus moved to so-called closed-loop PHS that could also use different fluids and be built underground, helping to reduce geographical constraints and the overall cost of this technology (He et al., 2021, pp. 2–4). PHS requires significant space and is only suitable for specific geographies where large bodies of water or other fluids at different heights can be created. In addition, the technology may cause adverse environmental consequences, such as the loss of natural habitats (Hoff, 2022, p. 79). However, this thesis aims to provide a universal overview of different storage technologies and their suitability for individual use cases. Therefore, the analysis excludes geographical, environmental, and social factors that could differ from region to region. Nevertheless, decision-makers should always reflect on them when determining the most suitable EES technology for their specific circumstances. PHS is a versatile technology used for short- to long-term energy storage. Initially, it mainly shifted large amounts of energy to later times of the day. However, It is also used for seasonal storage and short-term applications like response services (Hoff, 2022, pp. 88–89).

CAES compresses air using electricity and stores it in tanks or underground reservoirs such as salt caverns. At discharge, it recovers electricity using turbines and generators as the air is expelled. To do this, the air must first be heated and expanded. This can be done either by using fossil fuels such as natural gas (diabatic compressed air energy storage (D-CAES)) or by taking waste heat from the compression process that is stored using thermal energy storage (adiabatic compressed air energy storage (A-CAES)). There is also a third technology (isothermal compressed air energy storage (I-CAES)) that is similar to A-CAES but keeps the temperature of the air constant throughout the entire process (He et al., 2021, p. 4). The basic principle of CAES is similar to that of PHS, and the two technologies share their suitability for various applications (Das et al., 2018, p. 1210). Generally, most mechanical storage technologies apart from FES can achieve high power levels while reaching discharge durations of more than one hour. On the negative side, these technologies respond relatively slowly and require much space due to their comparatively low energy densities, which may make them less attractive for some applications (He et al., 2021, pp. 7–8).

Instead of potential energy, FES stores electricity in the form of kinetic energy in a rotating mass (flywheel). Charging and discharging are done by a device that is a combination of a motor and a generator that accelerates and decelerates the wheel. The flywheel spins in a vacuum chamber and is held in place by magnetic bearings to reduce energy losses due to friction. However, this also consumes some energy and therefore takes up some of the available capacity of a flywheel (Hoff, 2022, p. 59). Depending on the rotational speed, FES technologies are categorized as low-speed flywheels (<10,000 rpm) and high-speed flywheels (>10,000 rpm) (Nadeem et al., 2019, p. 4558). Unlike PHS and CAES, FES is unsuitable for long-term applications (Aneke & Wang, 2016, pp. 355–356). Like other mechanical storage technologies, FES has significantly longer lifetimes and higher cycle lives than other forms of energy storage. Conversely, they have lower energy densities than electrochemical or chemical storage technologies. FES can still achieve high power densities and has some of the highest round-trip efficiencies (RTEs) of any mechanical storage technology. The fast reaction times render it suitable for short-term use cases such as frequency control or power quality (He et al., 2021, pp. 7–8).

2.2.2. Electrochemical Storage Technologies

Electrochemical storage is one of the oldest forms of EES (Hoff, 2022, p. 3). This technology uses electrochemical reactions to convert electrical energy into chemical energy or vice versa (He et al., 2021, p. 2). According to China Energy Storage Alliance (CNESA) (2020), just four technologies account for more than 99 % of the world's installed electrochemical storage capacity (see Figure 1). All of them belong to the group of battery energy storage (BES) (Zakeri & Syri, 2015, p. 579).

These four technologies are lead-acid (PbA), lithium-ion (Li-ion), sodium-sulfur (NaS), and flow batteries, while vanadium redox flow batteries (VRFBs) are the most common chemistry of flow batteries, according to Aneke and Wang (2016, p. 372). Although numerous other chemistries exist, most available LCOS studies often focus on these four BES technologies. Therefore, PbA, Li-ion, NaS, and VRFB are the only electrochemical storage technologies considered here.

PbA batteries, invented over 150 years ago, are a well-established and mature rechargeable battery technology. They are made up of a lead dioxide (PbO_2) anode and a lead (Pb) cathode that are covered by an electrolyte consisting of a sulfuric acid (H_2SO_4) solution. Charging and discharging rely on reversible redox reactions known as the double sulfate reaction. PbA can be categorized into two main types: vented (flooded) lead-acid batteries (VLA) and valve-regulated (sealed) lead-acid batteries (VRLA/SLA). These batteries find applications in various fields, such as emergency backup power and different types of grid services (Nadeem et al., 2019, pp. 4564–4565). A major drawback of a PbA battery is its rapid capacity degradation. To mitigate this problem, it is common practice to discharge the battery only partially. Consequently, PbA batteries exhibit a comparably low depth of discharge (DoD). As a result, a PbA system's rated energy must be considerably higher than the required energy as the actual usable capacity is much lower than the theoretical capacity of the system. Moreover, the rapid capacity degradation also leads to a relatively short cycle life for PbA batteries (Hoff, 2022, pp. 156, 162).

The name Li-ion stems from the operating principle of this technology: during charging or discharging, Li^+ ions migrate between a cathode, typically composed of lithium metal oxide, and an anode, most commonly consisting of graphite. Like PbA batteries, these two electrodes are covered by an electrolyte that facilitates the movement of the Li^+ ions (He et al., 2021, p. 5). Li-ion battery performance can vary depending on the choice of materials and cell design, offering great flexibility and suitability for various applications such as frequency services, energy shifting, and energy arbitrage. However, this variability often involves trade-offs between different performance characteristics. Despite this, Li-ion batteries have gained significant recognition among the general public, primarily due to their popularity in the EV industry (He et al., 2021, p. 5). The high energy density allows for compact designs, making them space-efficient. While Li-ion only accounted for about 5% of the global storage capacity in 2020, this EES technology will likely become the market leader, overtaking PHS soon (Hoff, 2022, pp. 175, 181, 198).

NaS batteries are a prominent example of high-temperature batteries. These are based on liquid active materials that require a temperature of about 300 °C to remain in a liquid state (Ralon et al., 2017, pp. 95–96). NaS batteries employ liquid electrodes, with the anode consisting of molten sodium and the cathode comprising molten sulfur. A solid

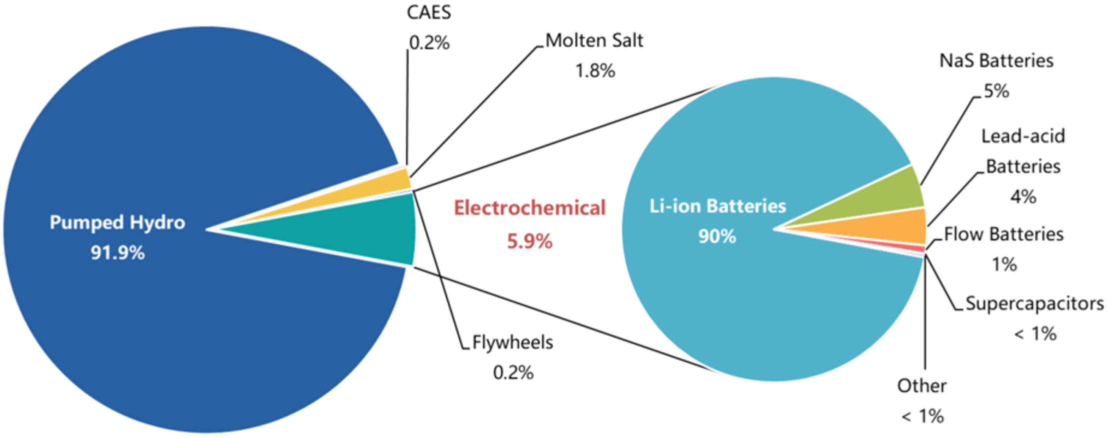

Figure 1: Distribution of Global Storage Capacity (China Energy Storage Alliance (CNESA), 2020)

Note. Molten Salt is a form of thermal energy storage.

beta alumina ceramic serves as both the separator and the electrolyte between the electrodes. During discharge, the molten sodium undergoes oxidation, resulting in the formation of Na^+ ions. These ions migrate through the solid beta alumina and react with the molten sulfur on the opposite side of the cell. This process reverses when the battery is charged. Being a high-temperature battery, NaS requires unique materials and a thermal management system that adds to the cost of the overall design (Nadeem et al., 2019, pp. 4566–4567). While NaS batteries exhibit lower RTEs than some other batteries and have a lower energy density than Li-ion, they possess minimal self-discharge and can achieve a relatively long lifetime. NaS batteries are often used for applications with cycles on a daily basis, such as peak shaving or energy arbitrage (Hoff, 2022, pp. 201–203).

Redox flow batteries (RFBs) are a distinct type of battery within BES technologies, differing from other BES systems in their design and operation. Unlike conventional batteries with a single cell containing two electrodes and an electrolyte, RFBs store energy in two liquid electrolyte solutions, the catholyte and anolyte (Hoff, 2022, p. 206). These electrolytes are stored in separate reservoirs. They are pumped into the cell during charging or discharging, where redox reactions occur. RFBs have similar advantages to other reservoir-based storage technologies, such as PHS or CAES. Examples include long lifetimes as well as decoupled energy and power storage. Consequently, they are technically well-suited for various large-scale stationary use cases. Furthermore, as BES technologies, RFBs exhibit higher RTEs than mechanical storage technologies (He et al., 2021, p. 6). Among RFBs, VRFBs are the most prevalent type. These batteries employ electrolytes of various vanadium ions dissolved in liquid acid solutions. One drawback of VRFBs is their reliance on pumps to circulate electrolytes between reservoirs and cells. The startup time for these pumps can take a few minutes, resulting in slower response times for the battery. Therefore, if the batteries need to respond quickly and unexpectedly, the pumps must run continuously, drawing power from the storage. This characteristic leads to lower RTEs than for other battery types (Hoff, 2022, pp. 205, 208).

2.2.3. Chemical Storage Technologies

Chemical storage technologies store electrical energy in chemical bonds (Long Duration Energy Storage Council [LDES Council], 2021, p. ix). These technologies are primarily based on alternative (non-fossil) fuels (He et al., 2021, p. 6). Among these, hydrogen is the most mature option. It can be used independently or in combination with carbon sources to produce methane, hydrocarbon, or methanol. However, these approaches are less developed. Moreover, there are additional energy losses when hydrogen is converted to other alternative fuels, which is why Aneke and Wang (2016, p. 359) suggest that hydrogen may have the highest potential. Therefore, this thesis will only focus on hydrogen energy storage (HES). Hydrogen is typically produced through water electrolysis, where electricity is employed to split water molecules into hydrogen and oxygen. The hydrogen can then be stored in tanks, usually either as a pressurized gas or as a cryogenic liquid (Fuel Cell Technologies Office, 2017), and converted back into electricity later. Fuel cells reverse the electrolysis process, which is the most common way to achieve this conversion. Alternatively, hydrogen can be burned in gas turbines to generate electricity (He et al., 2021, pp. 6–7). Due to its ability to be stored for extended periods, HES is particularly well-suited for seasonal storage or other long-term use cases (Nadeem et al., 2019, p. 4562). Chemical storage boasts higher energy densities compared to other storage technologies. Alternative fuels such as hydrogen are easily moveable from one location to another, and storage capacity can be increased independently of power generation (Gür, 2018, p. 2732). However, substantial energy losses are involved in converting electricity to hydrogen and back to electricity. Consequently, HES has an RTE of only 10-40 %, which is lower than that of mechanical storage and BES technologies (often about 45-95

%, depending on the specific technology) (He et al., 2021, p. 8).

2.3. Levelized Cost of Storage (LCOS)

With the increasing importance of energy storage, there has been a rise in studies analyzing the cost of storage. Many of these studies compare the total investment required for different storage technologies (Schmidt et al., 2019a, p. 81). While this metric may be relatively straightforward to calculate, it overlooks essential aspects that can significantly affect the economic suitability of a particular technology for a specific use case. For instance, the total investment cost fails to fully consider factors such as the RTE of a technology, the time value of money, or the expenses associated with operating and maintaining the storage system. This becomes particularly problematic when investment costs decrease due to experience or economies of scale, making them a smaller portion of the total cost (Schmidt et al., 2019a, p. 86). Therefore, there is a growing need for a metric that provides a holistic view of all relevant cost types incurred by an EES technology throughout its lifespan when used for a specific application. This includes taking into account the unique characteristics of each storage technology and the technical requirements of a given use case. The LCOS is one such metric that aims to encompass various factors to determine the actual cost of a particular technology. Therefore, it has gained international recognition as an index for assessing the cost of energy storage (Xu et al., 2022, p. 2) and has been employed in both academic and industrial settings (Beuse et al., 2020a, p. 2175).

2.3.1. General Concept

LCOS is a metric representing an EES technology's total discounted lifetime cost divided by its total discharged energy. Essentially, it provides the average price of released energy required to cover all lifetime costs of the technology such that the resulting net present value (NPV) of the investment would be zero (He et al., 2021, p. 10). LCOS is commonly expressed in dollars per MWh of discharged energy, although the currency and energy unit prefix may vary from study to study. In cases where power output is more significant than total energy released, the unit may be expressed as dollars per MW (Zakeri & Syri, 2015, p. 579). Although there are variations in terminology, such as Levelized Cost of Energy Storage (LCOES) (Comello & Reichelstein, 2019, p. 2) or Levelized Cost of Energy (LCOE) (Zakeri & Syri, 2015, p. 573), these terms generally refer to the same or very similar concepts when applied in the context of energy storage. As mentioned, LCOS accounts for application-specific parameters such as annual cycles or DoD. Consequently, the estimated cost of a particular technology may vary depending on the use case. Therefore, LCOS can only be used to compare the economic suitability of different EES technologies for a specific application but not for comparisons across multiple use cases (Schmidt et al., 2019a, p. 83).

2.3.2. LCOS Formula

There is no universal formula for determining the LCOS of EES technologies. Instead, the specific calculations made in different LCOS studies tend to vary slightly. However, the fundamental structure is consistent across studies, comprising three main aspects in almost every LCOS formula. Equation (1) summarizes these components[2].

$$LCOS = \frac{\sum_{t=0}^{T} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E\_discharged_t}{(1+r)^t}} \tag{1}$$

$CAPEX_t$ represents the capital expenditure (CAPEX) incurred in period t for setting up an EES technology. This includes factors such as equipment, construction materials, transportation, geological surveys, environmental impact studies, and installation costs. Depending on the specific technology, the composition of CAPEX can vary considerably. For example, installation costs are significant for PHS, while batteries may have a larger portion of the investment cost attributed to rare and expensive materials (Hoff, 2022, pp. 244–257). The actual set of factors included in CAPEX varies among LCOS studies. Some assume that CAPEX is only the upfront cost (Cortez et al., 2021, p. 208). In this case, equation (1) simplifies to equation (2). However, other studies also consider replacement cost or end-of-life cost as part of CAPEX that occur in later periods and therefore need to be discounted using the discount rate r (Jülch, 2016, pp. 1596–1597; Schmidt et al., 2019a, p. 82; Xu et al., 2022, p. 7).

$$LCOS = \frac{CAPEX_0 + \sum_{t=0}^{T} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E\_discharged_t}{(1+r)^t}} \tag{2}$$

$OPEX_t$ includes all ongoing operational expenditure (OPEX) required to run an EES system in period t. It typically contains costs related to plant operation and maintenance (O&M). While CAPEX is usually a more significant cost driver of the LCOS, OPEX is still a vital part of the calculation. This is especially true for technologies with steep learning curves like BES (Hoff, 2022, p. 257–261). Although the cost of charging electricity could be a substantial factor in OPEX, it is not considered in every study (Moradi-Shahrbabak & Jadidoleslam, 2023, p. 1700). Finally, $E\_discharged_t$ represents the total energy[3] discharged in period t. The value of $E\_discharged_t$ varies depending on the application and

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[2] Equations (1) and (2) are taken from Hoff (2022, p. 244) and slightly adjusted to generalize the LCOS formulas of the analyzed studies in Chapter 3.

[3] As this study focuses on electrical energy storage, $E\_discharged_t$ is the total electricity discharged in period t.

factors such as the number of annual cycles or the required energy capacity of the EES technology (Schmidt et al., 2019a, p. 96).

The input parameters for the LCOS formula are influenced not only by the application under consideration but also by the choice of storage technology. Technical characteristics such as RTE, DoD, self-discharge, annual degradation rate, or cycle life directly affect the abovementioned components (Long Duration Energy Storage Council [LDES Council], 2021, p. 49). For example, a lower RTE increases the amount of energy that needs to be charged, resulting in higher charging costs and, therefore, higher OPEX (if included in the OPEX calculation). At the same time, it reduces the available capacity of an EES technology and, therefore, may require oversizing the rated capacity, driving up the CAPEX. Consequently, $CAPEX_t$, $OPEX_t$, and $E\_discharged$ are again dependent on several parameters and described by formulas. However, since most studies differ in the choice of factors in their calculations, it is impossible to provide a general formula for these components. After calculating $CAPEX_t$, $OPEX_t$, and $E\_discharged_t$ for each period t during the project life T, they are discounted using the interest rate r and summed up. Finally, the sum of all discounted $CAPEX_t$ and $OPEX_t$ is divided by the total discharged electricity to compute the LCOS of an EES technology for a specific application.

3. Systematic Review of LCOS Studies

This thesis analyzes several LCOS studies to answer which technology is the most cost-effective for each stationary application. The goal is to determine whether the studies' suggestions regarding the cheapest EES technology for different use cases are consistent and to identify why studies might deviate from these patterns. To do this, reliable LCOS studies comparing the EES technologies described above for the applications under consideration first had to be identified and reviewed. This process is described in the following section.

3.1. Description of Methodology

To reduce potential bias and to make the identification and analysis of LCOS studies as objective as possible, a systematic review was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as underlying guidelines (Page et al., 2021). Due to the nature of this thesis, not all PRISMA rules were applicable or necessary and were therefore not considered here.

For a study to be included in this analysis, it must: (1) calculate the LCOS of individual storage technologies[4], (2) compare at least two of the technologies that are considered in this thesis, (3) examine at least one of the applications described above[5], (4) have a publication year of 2019 or later, (5) be written in English or German, and (6) be the most recent version. In addition, to ensure high overall quality, the journals of the considered articles must have a quartile ranking based on the Journal Impact Factor of Q2 or better or have an h-index of more than 30.

After defining the inclusion criteria, potentially relevant literature was identified in three steps. First, the academic database Scopus[6] was used for the literature search. The advantage of this database is that all indexed articles are peer-reviewed, which ensures a high baseline quality of the literature. A search string was developed based on the main aspects of the research question - EES storage and EES technologies, stationary applications, and LCOS - while including several synonyms and related terms in English and German. Two searches with slightly modified search strings were conducted on 4 and 5 May 2023. The exact queries used in Scopus can be found in Appendix B. The results were filtered to exclude review articles and include only records published after 2018 and written in English or German to obtain the most relevant and recent articles. These two searches yielded a total of 108 records, not including duplicates. An initial screening process excluded 79 of these records after applying the inclusion criteria to their titles and abstracts. Finally, the full texts of the remaining documents were reviewed, resulting in eleven studies that met all criteria. Second, a forward and backward search based on the final studies from the first step was conducted on 22 May 2023. This was done by evaluating those articles that either referenced or were cited by one of the eleven studies and were indexed in Scopus. The inclusion criterion for the accepted years of publication was adjusted to a lower limit of 2013 to account for the fact that referenced studies are necessarily older than the study they are referencing. This second step of the search strategy added another five studies to the total pool. Finally, Google[7] was used throughout May 2023 to further expand the set of LCOS studies and include gray literature, resulting in two additional reports. The literature search identified a total of 18 eligible studies (refer to Appendix D for an overview of all included studies). Figure 2 shows the process and reasons for exclusion.

Once the included articles and reports were identified, information relevant to determining the cheapest technologies and comparing the studies was collected from them. A data extraction template was created to standardize and objectify this process. The variables for which information was retrieved can be classified as characteristics, input parameters, and outcome variables. The authors, year of publication, methodology used, and technologies and applications evaluated are examples of study characteristics. Variables such as RTE or energy and power ratings are input param-

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[4] The name specified in the study does not have to be LCOS as long as the general principle aligns with the one described in Section 2.3.

[5] It is sufficient if the results for specific applications of interest can be derived. Therefore, also studies that provide LCOS for a range of input parameters without referring to specific use cases can be included.

[6] https://www.scopus.com/.

[7] https://www.google.com/.

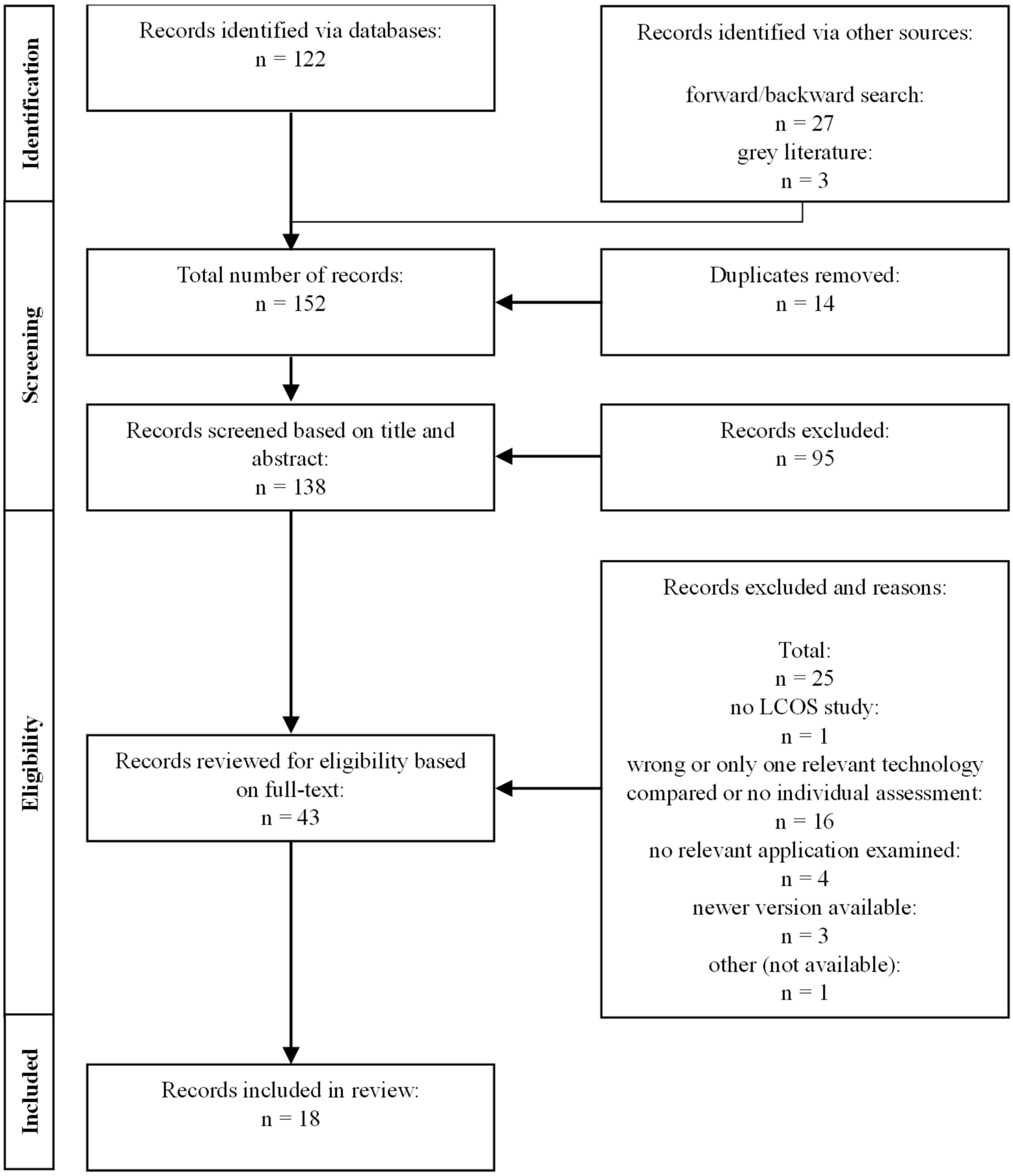

Figure 2: PRISMA Flow Chart (Adapted from Ramos-Martín et al. (2023, p. 4, Fig. 1))

eters, while LCOS and related concepts are the assessed outcomes. Please refer to Appendix C for a complete overview of the data extraction table.

Initially, only those studies that examined specific applications were analyzed (see Appendix D.1). The information on the input parameters drawn from these studies was then used to develop a general definition of all relevant applications, as shown in Table 1. This was done by taking all studies' overall minimum and maximum values and calculating the average of the means or most likely values (base case) given for individual parameters. If a study provided only a range of values, the minimum and maximum of this range were used to calculate the average. Only three critical determinants of a use case were considered to make the definition applicable to a wide range of studies. These are power rating, discharge duration, and number of annual cycles. Other factors, such as the required effective energy capacity (power times discharge duration), can often be derived from these. However, some studies did not provide values for all these parameters, leading to a potential bias in the definition from Table 1 and, therefore, in the analysis of the remaining studies described below.

Applications with similar technical characteristics were grouped as they would yield similar LCOS. Energy arbitrage and energy shifting were assigned to their parent category of time shifting. While peak shaving is the parent category of T&D investment deferral and demand charge management, the definition of peak shaving used by Nikolaidis et al. (2019, p. 756) is closer to time shifting (high power rating, medium discharge duration, medium number of annual cycles) than

Table 1: Definition of Applications

Application	Power [MW]			Discharge Duration [h]			Cycles [1/a]			Study IDs
	Min	Base Case	Max	Min	Base Case	Max	Min	Base Case	Max	
Primary Response	0.1	97.3 (181.1)	2,000.0	0.02	0.3 (0.1)	1.0	250.0	3,373.5 (2813.3)	15,000.0	2, 10, 11, 12, 14, 18
Secondary Response	1.0	152.9 (207.1)	2,000.0	0.3	1.0 (0.2)	24.0	20.0	617.5 (241.7)	1,000.0	3, 11, 14, 18
Tertiary Response	5.0	302.5 (202.5)	1,000.0	1.0	3.5 (0.5)	5.0	10.0	255.0 (245.0)	500.0	11, 14
Power Quality	0.1	104.6 (200.3)	1,000.0	0.003	0.3 (0.1)	0.5	10.0	1,309.3 (1872.9)	5,000.0	2, 11, 12, 14, 18
Time Shifting (incl. Peak Shaving)	0.001	223.1 (220.7)	2,000.0	1.0	5.4 (1.8)	24.0	50.0	364.0 (157.9)	730.0	2, 3, 11, 12, 14, 18
T&D Investment Deferral	1.0	31.4 (39.7)	500.0	0.5	4.8 (2.4)	8.0	10.0	274.3 (56.5)	500.0	2, 12, 14, 18
Demand Charge Management	0.001	1.0 (-)	10.0	1.0	4.0 (-)	6.0	50.0	500.0 (-)	500.0	14
Black Start	0.1	280.0 (270.0)	1,000.0	0.3	2.0 (1.0)	4.0	1.0	6.5 (3.5)	20.0	11, 14
UPS	0.002	5.0 (-)	10.0	0.3	0.4 (-)	0.5	50.0	50.0 (-)	50.0	11
Emergency Backup & Power Reliability	0.001	3.0 (2.0)	10.0	2.0	6.0 (2.0)	10.0	50.0	50.0 (0.0)	400.0	11, 14
Seasonal Storage	10.0	302.5 (202.5)	2,000.0	24.0	398.0 (302.0)	2,000.0	1.0	3.5 (0.5)	5.0	11, 14

Note. Study IDs are specified in Appendix D. Values in parentheses are standard deviations. Additional digits were added to numbers that would otherwise be displayed as zero.

to its sub-applications. Therefore, this definition of peak shaving was assigned to time shifting. Additionally, emergency backup and power reliability were combined into one category. No study analyzed inertial support, so it was excluded from the analysis. Moreover, Xu et al. (2022) were not included in the definition because this study examined three different real-life projects in China rather than providing a general overview of the technical requirements of the applications evaluated. As this was the only other study that explicitly considered peak shaving, this application was also excluded from further analysis. Next, an overview of the technical suitability of each EES technology for the applications under consideration was created (see Table 2) by listing all technologies examined for a specific application in at least one of the LCOS studies analyzed. Finally, the remaining LCOS studies' data (see Appendix D.2) was extracted using the assumptions from Table 1 and Table 2.

3.2. Results

Table 3 summarizes the most cost-effective EES technologies for each application and study[8]. A first look at these results indicates the presence of heterogeneity among the different studies rather than a consensus on the optimal technology for each application. It is worth noting, that a single study often limits its recommendations to only one or two technologies for different use cases. Nevertheless, no single technology is consistently recommended across all studies for any application. Instead, up to five EES technologies have been proposed for one examined application, such as primary response or time shifting. Each of the technologies considered appeared at least three times. However, Li-ion and PHS stand out as particularly prominent recommendations, accounting for more than half of all suggestions, with shares of 29 % for Li-ion and 26 % for PHS (see Figure 3)[9].

To identify potential patterns in the results, the data was sorted by input parameters (power rating, discharge duration, and annual cycles), and the shares of each technology were computed. Initially, the applications were sorted based on the average discharge duration of each use case. Figure 4 displays the distribution of EES technologies as the cheapest option for each application. Despite the sorting, considerable variation is observed, suggesting that the results may not strongly correlate with the discharge duration. However, each study employs its own set of assumptions, which can

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[8] A more detailed overview of the results is provided in Appendix C.

[9] Whenever two technologies were tied for one study and application, each technology was considered half a suggestion for calculating the shares.

Table 2: Technical Suitability of EES Technologies

Application	EES Technology							
	PHS	CAES	FES	PbA	Li-ion	NaS	VRFB	HES
Primary Response			10, 14, 18	2, 10, 11, 12, 14, 18	2, 10, 11, 12, 14, 18	2, 11, 12, 14	2, 10, 12, 14	14
Secondary Response	14	14, 18	11, 14	3, 11, 14, 18	3, 11, 14, 18	11, 14, 18	3, 11, 14, 18	14, 18
Tertiary Response	14	14		11, 14	11, 14	11, 14	11, 14	11, 14
Power Quality			11, 14, 18	2, 11, 12, 14, 18	2, 11, 12, 14, 18	2, 11, 12, 14	2, 12, 14	14
Time Shifting	11, 14, 18	11, 14, 18		2, 3, 11, 12, 14, 18	2, 3, 11, 12, 14	2, 11, 12, 14, 18	2, 3, 11, 12, 14, 18	11, 14
T&D Investment Deferral	14	14, 18		2, 12, 14, 17, 18	2, 12, 14, 17, 18	2, 12, 14, 18	2, 12, 14, 17, 18	14, 18
Demand Charge Mangagement				14	14	14	14	14
Black Start	14	14	14	14	14	14	11, 14	11, 14
UPS				11	11			
Emergency Backup & Power Reliability				11, 14	11, 14	14	14	14
Seasonal Storage	11, 14	11, 14					14	11, 14

Note. The numbers refer to the Study IDs shown in Appendix D.

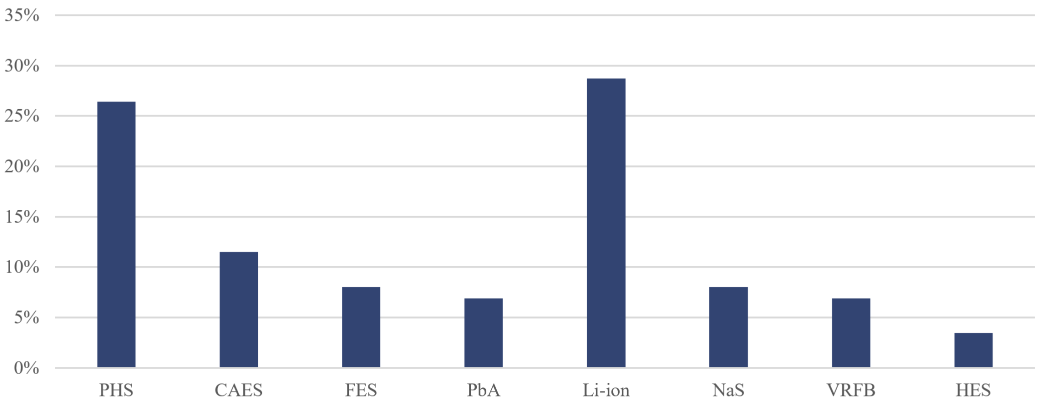

Figure 3: Shares of EES Technologies in Overall Results

result in significant variations in the input parameters for a given application compared to those outlined in Table 1.

To address this variability between studies, the results were categorized into five mutually exclusive and collectively exhaustive discharge duration intervals ([0 h; 1 h), [1 h; 4 h), [4 h; 8 h), [8 h; 24 h), [24 h; 700 h]) according to the assumed discharge duration in each study and thus independent of the application examined[10]. Figure 5 illustrates the distribution of shares for each duration interval.

As a result of this categorization, a new pattern emerges, suggesting a dependency on discharge duration. Li-ion and FES have the largest shares among the EES technologies for durations of less than one hour. Li-ion continues to dominate for medium discharge durations, while PHS gradually replaces FES and reaches a peak share of 50 % in the 8–24-hour interval. In the case of very long discharge durations, CAES becomes the dominant technology, accounting for 75 % of the studies' recommendations, with PHS being the only other economically viable option. These observations are further clarified in Figure 6, showing that only PHS, CAES, FES, and Li-ion have shares exceeding 20 % in any interval.

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[10] Studies without information about the assumed discharge duration were not considered in this categorization.

Table 3: Most Cost-Effective EES Technologies for Each Application and LCOS Study

Study ID	Application										
	Primary Response	Secondary Response	Tertiary Response	Power Quality	Time Shifting	T&D Investment Deferral	Demand Charge Management	Black Start	UPS	Emergency Backup & Power Reliability	Seasonal Storage
1		PHS	Li-ion/VRFB		PHS	Li-ion/VRFB					
2	Li-ion			Li-ion	NaS	NaS					
3		Li-ion (LFP/ NCA)			Li-ion (LFP)						
4	Li-ion	Li-ion	PHS	Li-ion	PHS	PHS	Li-ion		Li-ion	Li-ion	
5	FES (Long-/Short-Duration)	Li-ion		Li-ion/FES (Long-Duration)			FES (Long-Duration)	Li-ion/FES (Long-Duration)	Li-ion		
6		Li-ion			HES (Underground)	Li-ion	Li-ion			Li-ion	
7		CAES (D-CAES)/ PHS			CAES (D-CAES)/ PHS						CAES (D-CAES)
8		PHS	PHS		PHS	PHS					PHS
9	VRFB	VRFB	PHS	VRFB	PHS			PHS	VRFB		
10	FES										
11	PbA (Advanced)	PbA (Advanced)	HES	PbA (Advanced)	PHS			HES	PbA	PbA	CAES
12	NaS			NaS	Li-ion	Li-ion					
13		CAES (D-CAES)			CAES (D-CAES)	CAES (D-CAES)	NaS			NaS	
14	FES	PHS	PHS	NaS	PHS	PHS	VRFB	PHS		PbA	CAES
15					PHS	PHS					
16		Li-ion (LFP)	CAES		Li-ion (LFP)	Li-ion (LFP)	Li-ion (LFP)				
17						Li-ion (LFP)					
18	FES	CAES (Aboveground)		FES	PHS	CAES (Aboveground)					

Note. Sub-groups of technologies are specified in parentheses. LFP = lithium iron phosphate; NCA = nickel cobalt aluminum oxide. The two cheapest technologies were taken for this table whenever there was no clear winner.

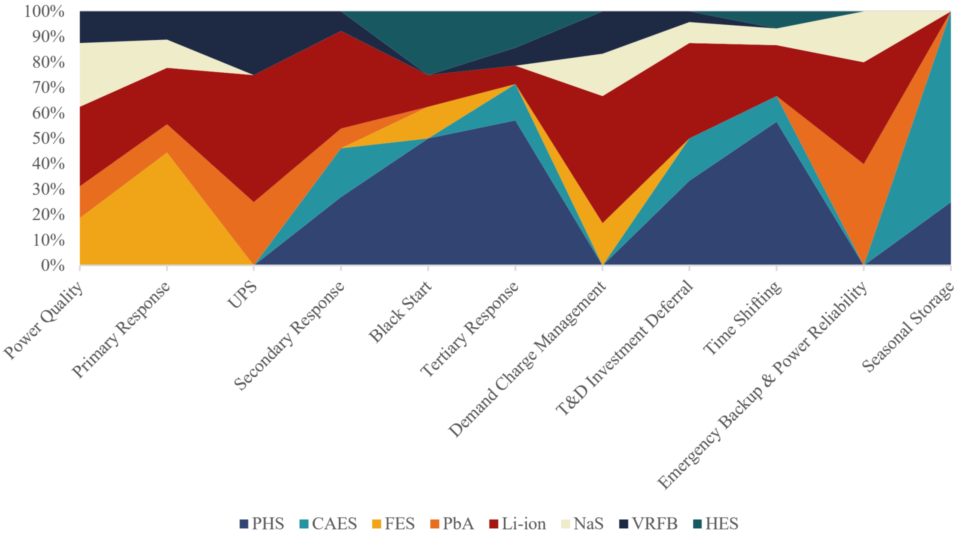

Figure 4: Shares of Results per Application, Sorted by Discharge Duration

Note. Ascending order from left to right.

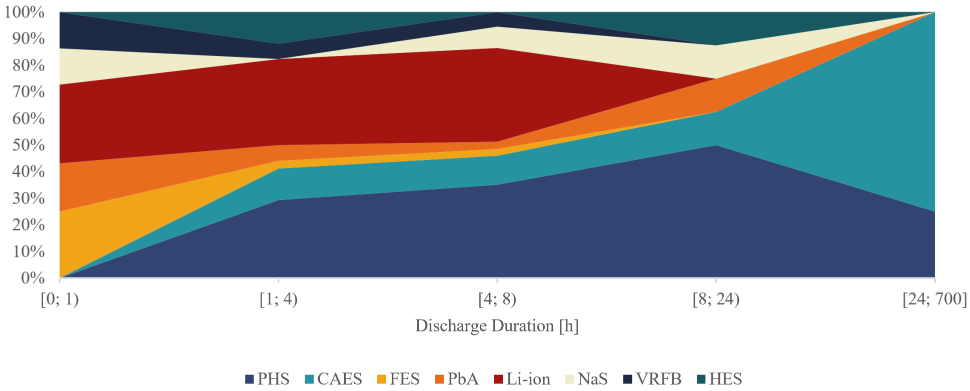

Figure 5: Shares of Results per Duration Interval

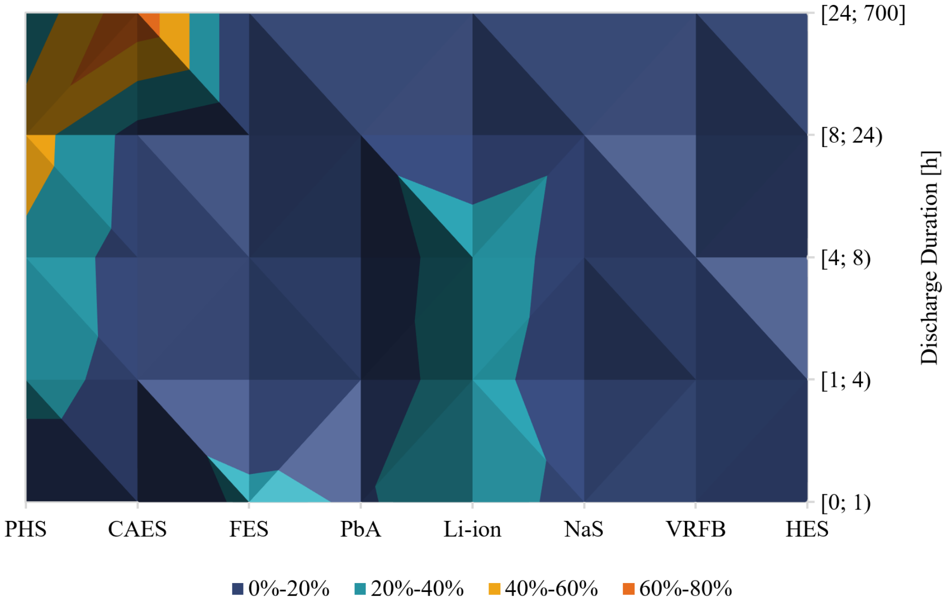

Figure 6: Contour Plot of Shares per Duration Interval

The same clustering approach was applied to power ratings and the number of annual cycles, detailed in Appendix E and Appendix F, respectively[11]. Plotting the shares of results based on power intervals (see Appendix E.2) leads to a somewhat similar structure as in Figure 5. Again, Li-ion and PHS dominate all power ranges, with the former having the greatest shares for low to medium power ratings and the latter taking over for medium to high power. Notably, PbA has the third largest share for the lowest and highest power intervals, with 12 % and 30 %, respectively.

Regarding the parameter of annual cycles, the shares of the results exhibit the most remarkable variation (see Appendix F.2). Most technologies, particularly PHS and Li-ion, appear to be viable over a wide range of frequencies, as depicted in Figure 7. Overall, PHS, CAES, and HES dominate low-frequency applications. While PHS remains strong for medium levels of annual cycles, CAES and HES are replaced by Li-ion, PbA, and NaS. Li-ion becomes even more prominent for higher frequencies, peaking at a 75 % share for 600 to 1,000 annual cycles. Only for high-cycle applications, FES supplants Li-ion as the dominant technology, accounting for 50 % of the results for frequencies between 1,000 and 8,000 cycles.

Finally, the studies' projections for the cheapest EES technologies in the future were examined. In this analysis, most studies indicate that Li-ion has a significant advantage over other EES technologies, representing at least 75 % of the results for all but two applications (see Figure 8). Only for the short-duration, high-frequency primary response application, Li-ion will continue to compete with FES, while for the long-duration, low-frequency seasonal storage application, HES is expected to be the most economical option in all studies that provided a forecast for this use case (Hunter et al., 2021; Jülch, 2016; Schmidt et al., 2019a).

3.3. Discussion

Upon examining the structured and visualized results, noticeable patterns emerge that allow for the development of general assumptions regarding the most cost-effective technology for each use case.

3.3.1. Short-Duration Applications

For applications with very short discharge durations, FES and Li-ion appear to be the most promising technologies (see Figure 6). Although UPS would fall into this category with an estimated average discharge duration of 0.4 hours (see Table 1), FES was not considered technically suitable for this application (see Table 2).

One notable advantage of FES technologies, as mentioned in Section 2.2.1, is their very high cycle life compared to other EES technologies. This is reflected in the analyzed LCOS studies, where FES exhibits an average cycle life of about 1,450,850 compared to 4,800 for Li-ion and 3,300 for PbA. The extended cycle life of FES can provide a cost advantage in high-frequency applications since flywheels require fewer replacements than other technologies. For instance, in the case of primary response, with an average project life of 14 years and a mean number of about 3,374 annual cycles, FES technologies would last 430 years without replacement, while Li-ion and PbA would require ten and 15 replacements, respectively[12]. Given this cost advantage, one might expect FES to consistently appear as the cheapest technology for primary response. However, only four out of nine studies suggest FES for this application (see Table 3). This discrepancy may be attributed to the set of technologies evaluated in each study for primary response. It can be noted that all studies that considered FES suggest it as the cheapest technology for primary response. Of course, the exclusion of FES in the other studies does not automatically imply that it would have the lowest LCOS if included. Nevertheless, combined with its cost advantage in high-frequency scenarios, this strongly indicates that FES may be the cheapest technology for primary response. As shown in Figure 8, Li-ion is expected to catch up in the future (Beuse et al., 2020b; Castro et al., 2022; Schmidt et al., 2019a), possibly due to its significant projected cost reduction (Schmidt et al., 2019b, Table S8) resulting from the widespread adoption of EVs as described in Section 2.2.2.

In the power quality application, FES is only recommended in two out of eight studies (see Table 3). Again, this could be partly due to the exclusion of FES in four studies considering this use case (Battke et al., 2013; Beuse et al., 2020a; Moradi-Shahrbabak & Jadidoleslam, 2023; Rahman et al., 2021). Nevertheless, although it was part of their considerations, Nikolaidis et al. (2019) and Schmidt et al. (2019a) do not propose FES for power quality. One possible explanation for the weaker performance of FES technologies in power quality is their comparatively high investment costs. Taking the average of all studies considering the technology (see Appendix D), FES has an energy-based CAPEX of 2,924 USD/kWh and a power-specific CAPEX of 477 USD/kW, compared to values of 381-583 USD/kWh and 331-885 USD/kW for BES technologies[13]. The estimated average number of annual cycles for power quality is more than 60 % lower than that of primary response. As a result, FES technologies may struggle to offset their higher initial investment costs with their cycle life advantage. This is especially true for the lower frequency range of only ten annual cycles, where no technology would reach its cycle life within the estimated project life of about 17 years. Nevertheless, FES could still be a viable option for power quality, especially for higher frequencies, as indicated by two studies recommending FES

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[11] Again, only studies with information about the categorizing input parameter were considered.

[12] The calendrical lives of 19, 12, and 10 years for FES, Li-ion, and PbA do not influence this result. It would be the limiting factor for FES, but it still lies above the project life.

[13] Assuming ten-year average (2013-2022) exchange rates of 0.8606 EUR/USD, 1.3129 AUD/USD, and 6.5580 CNY/USD (Organisation for Economic Co-operation and Development (OECD) (2023)) and without considering inflation. These assumptions also apply to all following CAPEX and OPEX comparisons.

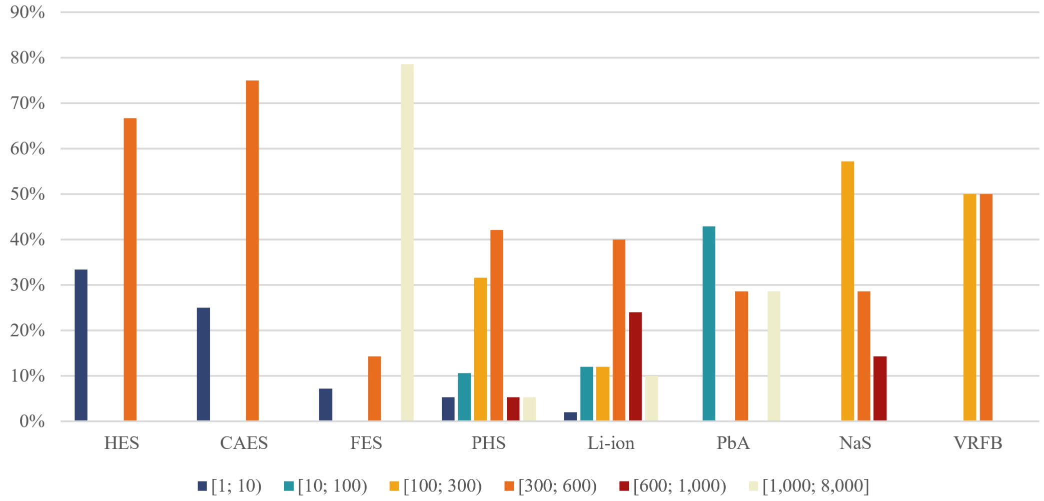

Figure 7: Shares of Cycle Intervals in the Results of Each EES Technology

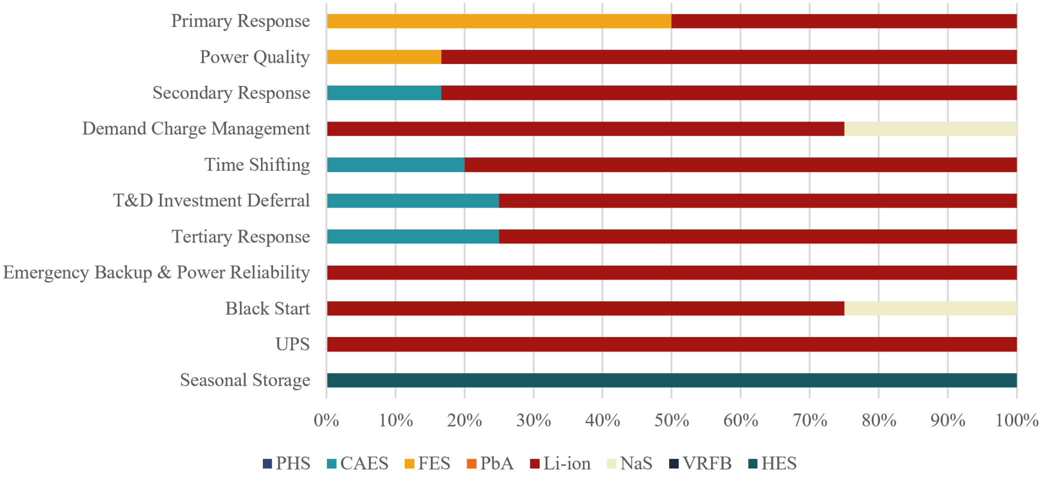

Figure 8: Most Cost-Effective EES Technologies in the Future

Note. Only Beuse et al. (2020a), Castro et al. (2022), Hunter et al. (2021), Jülch (2016), Schmidt et al. (2019a), and Viswanathan et al. (2022) provided future projections.

for this application assuming more than 1,000 annual cycles (Castro et al., 2022; Zakeri & Syri, 2015).

There is a clear trend toward BES for power quality, with over 80 % of study results favoring this group of storage technologies. Moradi-Shahrbabak and Jadidoleslam (2023) conclude that VRFB is the cheapest BES technology. However, this study lacks transparency regarding the input parameters used, as it only provides ranges, which even differ between the technologies. This makes it unclear which values were used for the LCOS calculation. While the study assumes a power range for VRFB of 0.01-3 MW, Li-ion can reach a power of up to 50 MW (Moradi-Shahrbabak & Jadidoleslam, 2023, p. 1704). Additionally, the study assumes low balance of system (BOS) and fixed O&M costs for VRFB compared to other technologies (Moradi-Shahrbabak & Jadidoleslam, 2023, p. 1705). This could lead to lower overall power-based costs for VRFB, making it the preferred technology. In addition, the study overlooks some vital cost factors, such as time and cycle degradation, further impacting the reliability of the results compared to some of the other studies. Nikolaidis et al. (2019) propose advanced PbA as the cheapest technology for power quality (voltage regulation). No other study considers this technology. Instead, they primarily refer to the classic VRLA battery. Furthermore, this study calculates LCOS on a power basis (USD/kW) rather than an energy basis (USD/kWh). As described in Section 2.3.1, this is a viable approach for applications where the ability to provide power is more significant than the total discharged energy. This is arguably the case for power quality. The EES technologies may not need to discharge large amounts of energy but must react quickly and precisely inject or absorb power to balance out voltage fluctuations. Without taking PbA into account, NaS is the cheapest technology in Nikolaidis et al. (2019), which is consistent with the findings of Rahman et al. (2021)

and Schmidt et al. (2019a). Overall, NaS and Li-ion emerge as the most prominent options for power quality. While it is difficult to determine the superiority of either technology at this stage, as there are detailed studies supporting both options (Beuse et al., 2020a; Schmidt et al., 2019a), Li-ion is expected to be the clear winner in the future (see Figure 8) (Beuse et al., 2020b; Castro et al., 2022; Schmidt et al., 2019a).

BES also appears to dominate the third use case with short discharge durations, namely UPS. Nikolaidis et al. (2019) was the only study that specifically defined this application, potentially leading to biased input parameters in Table 1 and influencing the results drawn from other studies. Furthermore, the study only compares two relevant technologies, PbA and Li-ion, which is why Table 2 limits this application to these two EES technologies. Generally, UPS can be seen as a customer service (Fitzgerald et al., 2015, p. 16) requiring a low power rating, which may be why mechanical storage is unsuitable here. However, technical characteristics provided by Schmidt et al. (2019b, Table S3) suggest that VRFB or NaS could also be suitable for UPS, even though Nikolaidis et al. (2019) did not consider them. In this context, Moradi-Shahrbabak and Jadidoleslam (2023) once more suggest VRFB, but the lack of transparency described above again makes it difficult to compare these findings with other results. Nikolaidis et al. (2019) propose PbA for UPS. As described above, this study uses LCOS on a power basis, which is an appropriate approach for UPS. Here, the value of the application mainly comes from providing power in the event of a system failure instead of the total amount of energy discharged. However, Nikolaidis et al. (2019) do not consider time or cycle degradation, which could be particularly beneficial for PbA, which typically suffers from high capacity degradation as described in Section 2.2.2. Drawing precise conclusions for UPS is challenging due to the limited number of studies and the potential bias in the definition of the application. In most cases, Li-ion appears to be the preferred technology, while PbA may also be a viable option. Only Beuse et al. (2020a) and Castro et al. (2022) provide future projections applicable to this use case, and both studies assume that Li-ion will be the most cost-effective technology.

3.3.2. Lower Intermediate Applications

For medium-duration applications, Li-ion shares its dominance with PHS (see Figure 5). While the latter takes over for upper intermediate durations and higher power ratings, Li-ion appears to be the most appropriate technology in relatively lower duration and power applications. Secondary response, demand charge management, emergency backup, and power reliability are examples of those medium-duration use cases on the lower end of the power ratings or discharge durations.

In the context of secondary response, Li-ion is the least expensive technology in five of 13 studies. PHS and CAES share the second place, each appearing three times (see Table 3). Australian Energy Regulator (AER) (2020) is one of the studies that suggest PHS for this application. However, this study has a regional focus on Australia. It incorporates financing and funding costs (AER, 2020, p. 7) that are not considered in most other studies and may vary significantly between regions. It also assumes that each EES technology can deliver its full rated capacity. This does not reflect the reality where energy is lost due to inefficiencies or capacity degradation over time, which is why the rated capacity often needs to be higher than the actual capacity required (AER, 2020, pp. 29–30). Similarly, self-discharge is not considered. End-of-life costs, including recycling efforts and potential revenue from salvage values, are essential factors not considered in the calculations of AER (2020). Different materials used in BES may require varying degrees of recycling effort (Battke et al., 2013, p. 248). Furthermore, this study lacks transparency regarding input parameters such as DoD, cycle or calendric life, CAPEX, OPEX, and BOS cost. This lack of transparency makes it challenging to compare the results with other studies and to understand the reasons for different outcomes. Most importantly, the study does not directly compare LCOS between different technologies but instead displays LCOS on separate graphs. Therefore, values need to be read from the graphs, which is very imprecise, especially when values are close together (AER, 2020, pp. 40–44). Consequently, it is impossible to draw precise and meaningful conclusions from this study.

One possible reason why studies like AER (2020), Hunter et al. (2021), Jülch (2016), and Salvini and Giovannelli (2022) suggest PHS or CAES instead of Li-ion for secondary response could be their assumption of longer discharge durations ranging from 4-12 hours, compared to the estimated average of one hour (see Table 1) for this application. PHS and CAES have significantly lower energy-based CAPEX than BES technologies (96-124 USD/kWh vs. 381-583 USD/kWh). Therefore, as the energy capacity increases, PHS and CAES become relatively more attractive, assuming all other factors remain constant. This is the case here since energy capacity is the product of discharge duration and power rating. Conversely, PHS and CAES have high power-based CAPEX of 983 USD/kW and 957 USD/kW, respectively, making them potentially more expensive than BES (331-885 USD/kW) for lower discharge durations assuming the same power ratings. Nevertheless, Schmidt et al. (2019a) and Zakeri and Syri (2015) propose PHS and CAES, even when assuming short discharge durations of 1 and 1.25 hours, respectively. One possible explanation is that Schmidt et al. (2019b, Table S6) use a shallow DoD assumption for Li-ion (57 %) compared to the 80-90 % (Castro et al., 2022, p. 357; Nikolaidis et al., 2019, p. 757) used in the other studies. A lower DoD increases the required nominal energy capacity to achieve the same effective energy output, driving up the LCOS of a technology. Zakeri and Syri (2015, p. 592) assume RTEs for CAES of 70-90 %, considerably higher than the typical range in other studies, which usually falls between 44 % (Beuse et al., 2020a, p. 2165) and 70 % (Jülch, 2016, p. 1599). LCOS is highly sensitive to changes in the RTE (Mugyema et al., 2023, p. 11), which could explain why this study identifies CAES as the cheapest technology. Moradi-Shahrbabak and

Jadidoleslam (2023) and Nikolaidis et al. (2019) are two more outliers, suggesting VRFB and advanced PbA, respectively. However, as mentioned earlier, these studies are less comparable, and they also did not consider CAES or PHS for secondary response.

In summary, except for Beuse et al. (2020a), who used comparatively low discharge durations, all studies that included CAES or PHS in their comparisons, suggested one of them as the cheapest technology. When increasing the assumed discharge duration to two hours, Beuse et al. (2020b) aligns with the other studies and recommends PHS. Therefore, PHS, CAES, and Li-ion are likely competitive options for secondary response, with PHS and CAES potentially being the preferred choice for relatively longer discharge durations. Looking to the future, most studies agree that Li-ion will be the dominant technology, outperforming PHS and CAES for this application (Beuse et al., 2020b; Castro et al., 2022; Hunter et al., 2021; Jülch, 2016; Schmidt et al., 2019a; Viswanathan et al., 2022).

The perspective changes when it comes to demand charge management. As a behind-the-meter customer service (Fitzgerald et al., 2015, p. 16), mechanical storage is unsuitable (see Table 2), and BES is the dominant technology. The most prominent representative of this group is, once again, Li-ion (see Table 3), but three studies are recommending other technologies. Castro et al. (2022) conclude that long-duration flywheels are the most suitable technology for applications such as demand charge management. However, long-duration flywheels are a relatively new and emerging technology (Castro et al., 2022, p. 355) not considered in the other studies. In addition, self-discharge is not taken into account. FES technologies have an average self-discharge of nearly 190 % per day[14], so not considering this could significantly affect the results. Salvini and Giovannelli (2022) identify NaS batteries as the cheapest technology for demand charge management. This finding may be influenced by the assumption of a higher power rating (5 MW, five times higher than other studies) and a longer discharge duration (six hours, 50 % higher). The average energy-based CAPEX of NaS used in all studies analyzed is the lowest at 346 USD/kWh compared to other BES technologies (381-583 USD/kWh). The higher power rating and longer discharge duration result in higher energy capacity requirements, which therefore have a proportionately lower impact on the LCOS of NaS, potentially making it the cheapest technology in this study. It is worth noting that Salvini and Giovannelli (2022) do not consider essential cost factors like replacement cost, end-of-life cost, cycle and time degradation, and self-discharge, which may affect the accuracy of the resulting LCOS estimates. Finally, Schmidt et al. (2019a) propose VRFB as the cheapest technology for demand charge management. The study assumes 500 annual cycles, which is at the upper end of the range for this application (see Table 1). One advantage of VRFB is its long cycle life compared to other BES technologies, lasting about twice as many cycles as Li-ion, PbA, or NaS in this study (Schmidt et al., 2019b, Table S3). This extended cycle life may be why VRFB is preferred in this analysis. Apart from that, this study demonstrates high overall quality, considering a wide range of cost factors and taking into account the uncertainty of their input parameters.

While it is difficult to draw definitive conclusions, Li-ion may have a slight advantage over other BES technologies for demand charge management, resulting in the lowest LCOS in 50 % of the studies. Nevertheless, NaS and VRFB could also be viable options, often ranked in the top three technologies. It is essential to acknowledge that the estimates of input parameters used for this application (see Table 1) are again only derived from the values of a single study (Schmidt et al., 2019b), increasing the risk of biased conclusions. In the future, 75 % of the studies predict that Li-ion will outperform all other technologies for this use case (Beuse et al., 2020b; Castro et al., 2022; Schmidt et al., 2019a; Viswanathan et al., 2022).

As for demand charge management, mechanical storage is unsuitable for emergency backup and power reliability (see Table 2), which may explain the dominance of BES solutions. The two most frequently proposed technologies for these use cases are Li-ion and PbA, each suggested by 40 % of the studies. Salvini and Giovannelli (2022) stand out as the only outlier, again identifying NaS as the cheapest technology. The reasons for this result are equivalent to those described earlier for demand charge management, as the same input parameters were used for both applications. For the studies favoring PbA (Nikolaidis et al., 2019; Schmidt et al., 2019a), a much lower cycle frequency was assumed than for the other studies (except for Beuse et al. (2020a)). PbA is less suitable for higher numbers of cycles due to cycle degradation (Hoff, 2022, p. 156). On the other hand, PbA is a relatively inexpensive technology compared to Li-ion[15]. At lower frequencies, cycle life and degradation are less critical, making investment cost one of the main drivers for the LCOS. Furthermore, studies favoring PbA over Li-ion assume comparatively higher RTEs for PbA (84-90 % (Nikolaidis et al., 2019, p. 757; Schmidt et al., 2019b, Table S4) vs. 72-79 % (Beuse et al., 2020a, p. 2165; Cortez et al., 2021, p. 209). For comparison, the range specified by IRENA falls somewhere in the middle at 80-82 % (Ralon et al., 2017, p. 125), so both assumptions appear similarly accurate. There are high-quality studies that consider a wide range of cost factors on either side (Beuse et al., 2020a; Schmidt et al., 2019a).

In summary, while there may be a variety of suitable technologies for emergency backup and power reliability applications, Li-ion and PbA appear to be particularly advantageous. Again, all studies agree that Li-ion will be the dominant technology in the future (Beuse et al., 2020b; Schmidt et al., 2019a), likely due to its stronger cost reduction (Schmidt et

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[14] Average calculated from the values provided by all studies that considered FES: Mugyema et al. (2023), Nikolaidis et al. (2019), Schmidt et al. (2019a), and Zakeri and Syri (2015).

[15] 381 USD/kWh and 583 USD/kW for PbA compared to 552 USD/kWh and 773 USD/kW for Li-ion.

al., 2019b, Table S8) and higher performance improvements (Ralon et al., 2017, p. 125). It is worth noting that both studies pointing to PbA (Nikolaidis et al., 2019; Schmidt et al., 2019a) were published four years ago, while Schmidt et al. (2019a, p. 87) even expected Li-ion to overtake PbA by 2020. Therefore, Li-ion may already be the single most cost-effective EES technology for these two use cases.

3.3.3. Upper Intermediate and Long-Duration Applications

After analyzing the lower intermediate applications, the remaining use cases in this overall category are examined. These are tertiary response, T&D investment deferral, time shifting, and black start. The goal is to get a better understanding of whether PHS may, in fact, be the most appropriate technology for them.

For tertiary response, 57 % of all studies considering this application concluded that PHS is the least expensive technology. CAES and HES come in second place, with one study each (14 %) suggesting them (see Table 3). Only one of the seven studies recommends BES technologies for this use case. In that study (AER, 2020), although it considered PHS, Li-ion and VRFB appear to be the cheapest options. As described in Section 3.3.2, this study's results are unreliable for this analysis due to regional focus, neglect of essential cost factors, lack of transparency, and omission of exact LCOS values for comparisons between different EES technologies.

Viswanathan et al. (2022, p. 130) conclude that CAES is the cheapest technology, while PHS ranks only fourth out of six, following Li-ion and VRFB. Like AER (2020), this research focuses on a specific region (USA). It takes into account taxes and financing costs, which again makes it less comparable to other studies and deviates from the aim of this thesis to provide a general and regionally independent view of the suitability of EES technologies. The LCOS of CAES (0.15-0.18 USD/kWh), Li-ion (0.14-0.20 USD/kWh), PHS (0.17-0.24 USD/kWh) and VRFB (0.17-0.23 USD/kWh) (Pacific Northwest National Laboratory (PNNL), 2023)[16] are fairly close. At the same time, it is unclear how much impact taxes and financing costs have on the total LCOS, so the technology rankings might be different if they were not considered. Except for AER (2020) and Viswanathan et al. (2022), all other studies that did not propose PHS for tertiary response did not consider it at all. Again, this does not automatically imply that PHS would be the cheapest technology if included in these studies. Nevertheless, it reinforces the overall impression that PHS is the dominant technology for tertiary response and has a slight advantage over other options, such as CAES or Li-ion. In terms of the future, Li-ion is the clear winner, as it is proposed by all but one study that provides a future projection for this use case (Beuse et al., 2020b; Jülch, 2016; Schmidt et al., 2019a; Viswanathan et al., 2022).

For T&D investment deferral, similar to tertiary response, AER (2020) suggests Li-ion and VRFB as the cheapest option, but as mentioned before, these results could be more reliable and precise. All other studies either recommend PHS or did not consider this technology. Mechanical storage seems to dominate for this application, with CAES being the cheapest technology when PHS is not included in the analysis. T&D investment deferral shares its future projections with tertiary response.

The dominance of PHS is even more apparent for time shifting, where it is the cheapest technology in all nine studies that considered it in their comparison. Including almost all studies (15 out of 18 (see Table 3)) in evaluating this application reduces the bias in the results. Therefore, PHS has a high probability of having a cost advantage in this particular use case. Similarly, Li-ion is likely to be the preferred choice in the future, with four out of five studies predicting that it will have the lowest LCOS (Beuse et al., 2020a; Hunter et al., 2021; Jülch, 2016; Schmidt et al., 2019a; Viswanathan et al., 2022).

Regarding black start applications, only four studies' results could be used to evaluate the techno-economic suitability of EES technologies for this use case (see Table 3). Additionally, only Nikolaidis et al. (2019) and Schmidt et al. (2019b) could be taken for defining the input parameters used in the remaining two studies, further limiting the reliability of the conclusions. PHS emerges as the winner in all studies where it was considered, underscoring the overall dominance of this technology for applications with upper intermediate discharge durations or power outputs. Only two studies provide future projections (Castro et al., 2022; Schmidt et al., 2019a), but they do not deviate from the consensus that Li-ion is the cheapest EES technology in most future scenarios. This supremacy can be attributed to the significant investments expected in Li-ion technologies, particularly in the EV industry, as discussed earlier. These investments enable economies of scale and accelerate learning effects (Beuse et al., 2020a, pp. 2166–2167), resulting in more significant cost reductions compared to the other technologies (Schmidt et al., 2019b, Table S8).

Seasonal storage is the only application where no study recommends BES. Instead, CAES and PHS are the only two technologies that appear at the top of the list. This is not surprising from an economic point of view, as the energy capacity requirements for seasonal storage of 240 MW to up to 4 GW[17] can be significantly higher compared to other use cases. As described in Section 3.3.2, PHS and CAES have a cost advantage over BES regarding energy-based CAPEX. This competitive advantage grows with the energy requirements of an application and is, therefore, highest for seasonal storage. From a technical perspective, except for VRFB, BES technologies are not considered applicable for this use case (see Table 2), which further explains their absence in the

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[16] An overview of the up-to-date LCOS values from Viswanathan et al. (2022) is given in Pacific Northwest National Laboratory (PNNL) (2023), which is why the latter was used here.

[17] When multiplying the lower and upper bounds of power and discharge durations, respectively (see Table 1).

recommendations. Jülch (2016) is the only study that suggests PHS for seasonal storage. One notable difference here is the assumption of a longer lifetime for PHS compared to the other three studies (80 years (Jülch, 2016, p. 1597) vs. 30-55 years (Hunter et al., 2021, p. 2093; Schmidt et al., 2019b, Table S4)). However, all of these values are within the bounds specified by IRENA (Ralon et al., 2017, p. 124), making it challenging to determine which study made more realistic assumptions, especially considering their overall similarity. In summary, CAES and PHS dominate the current state of seasonal storage, while HES is the clear winner for the future, being the only technology proposed for this use case (Beuse et al., 2020a; Hunter et al., 2021; Jülch, 2016; Schmidt et al., 2019a).

3.3.4. Most Cost-Effective EES Technologies

By evaluating the outcomes for each use case and considering the array of studies, it is possible to answer the fundamental question of this thesis: Which technology is most cost-effective for each application? In cases like demand charge management, UPS, emergency backup, and power reliability, which are typically behind-the-meter customer services, Li-ion emerges as the most suitable and cost-effective option overall. However, other BES technologies like PbA, NaS, and VRFB show promise and may be the preferred choice for specific individual use cases. Mechanical storage is not well suited for these applications. This also applies to power quality[18], where Li-ion and NaS have been identified as the most cost-effective options. PHS demonstrates dominance in the mid-range applications of secondary response, tertiary response, T&D investment deferral, time shifting, and black start, with CAES often a competitive alternative. For primary response, FES technologies exhibit a cycle life advantage, potentially making them the cheapest option overall, despite varied inclusion across studies. However, Li-ion is expected to catch up in the future. BES is not recommended for seasonal storage, where CAES and PHS are the top choices. Looking ahead, Li-ion is projected to increase its dominance, becoming the most suitable technology in all use cases except for seasonal storage, where HES is predicted to be the most cost-effective option. This is primarily due to Li-ion's expected cost reductions and performance improvements driven by extensive investments. In conclusion, the optimal energy storage technology varies across use cases, with PHS and Li-ion emerging as the most prominent and versatile options - one of these technologies being among the cheapest in almost all applications. Table 4 provides an overview of the most appropriate technologies for each application and period.

While the above paragraph answers the question of which technology is most cost-effective for which use case, it is essential to note that these conclusions largely depend on the application definitions used to extract data from the LCOS studies (see Table 1). These definitions are based on a sample of studies and may not reflect the true nature of these applications. This is particularly the case for demand charge management and UPS, where only one source was useable to estimate the input parameters. To allow for broader applicability of the findings and to reduce their dependence on specific use case definitions, Figure 9 provides a more general overview of the results that also reflects the input parameters assumed for each application. This also makes it possible to verify the observations and assumptions made in Section 3.2.

Figure 9 shows that FES and Li-ion dominate short-duration, high-frequency applications with discharge durations of less than one hour. While FES is only viable for several thousand cycles per year, Li-ion and other BES technologies are suitable for frequencies as low as 50 cycles to more than 1,000 annual cycles. This is consistent with the observations in Figure 5 and Appendix F.2. Discharge durations of about one hour form a transition zone where both BES as well as PHS and CAES are suitable technologies. From then on, the two mechanical storage technologies are the best option for almost all applications. Only for smaller use cases, with power ratings below 10 MW, can BES maintain its position as the cheapest EES technology. This differs from the initial assumptions made in Section 3.2 based on Appendix E.2. Finally, most technologies are indeed suitable for a wide range of annual cycles. In addition to the wide frequency range of BES, mechanical storage without FES can be economically viable in applications ranging from 600 to less than ten yearly cycles. This also confirms the general trend that BES is more suitable for medium to high frequencies, while mechanical storage takes over for medium to low frequencies, which aligns with the findings of Figure 7 and Appendix F.2.

While these general conclusions increase the usability for decision-makers by being less dependent on the definition of specific use cases, one should note that the LCOS is no law of nature, and the results rely on a series of studies that build their estimates on assumptions and simplifications of the real world. These findings can serve as guidelines, but the high uncertainty associated with estimating LCOS must be kept in mind. In addition, the cost is only one side of the economic viability coin. An EES technology must also create value by generating revenues or reducing other expenses to justify an investment. Some technologies could simultaneously be used for multiple applications, creating value from different sources (Ralon et al., 2017, p. 13). This could give them a comparative advantage, even though they may be more expensive than other technologies that are only useable for one application at a time. A goal of future research could be to develop a more holistic metric that considers both costs and economic value.

4. Conclusion

The objective of this thesis was to provide valuable assistance to decision-makers, policymakers, and other stakeholders in selecting EES technologies for specific applications. Various LCOS studies were analyzed and compared using a

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[18] Except for FES, which is a suitable technology for power quality.

Table 4: Most Cost-Effective EES Technologies for Each Application and Period

Application	Period	
	Present State	Future
Primary Response	FES	Li-ion/FES
Power Quality	Li-ion/NaS	Li-ion
UPS	Li-ion/PbA	Li-ion
Secondary Response	PHS/CAES/Li-ion	Li-ion
Demand Charge Management	Li-ion/NaS/VRFB	Li-ion
Emergency Backup & Power Reliability	Li-ion/PbA	Li-ion
Tertiary Response	PHS	Li-ion
T&D Investment Deferral	PHS	Li-ion
Time Shifting	PHS	Li-ion
Black Start	PHS	Li-ion
Seasonal Storage	PHS/CAES	HES

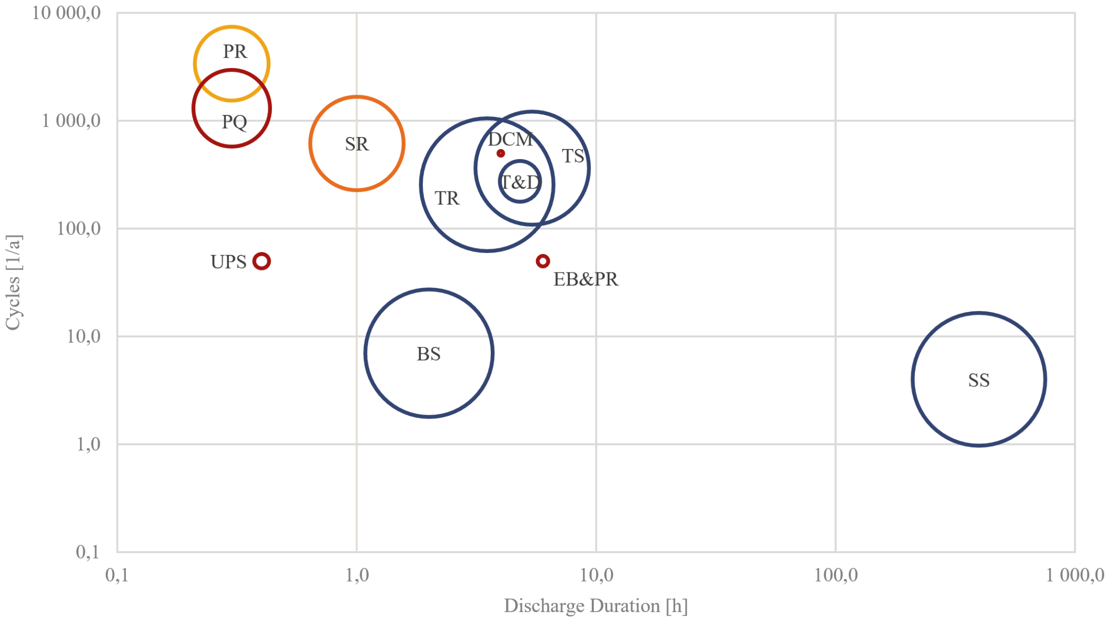

Figure 9: Most Cost-Effective EES Technologies in Dependence on Input Parameters

Note. Bubble sizes represent power ratings; Bubble color represents EES technology: Yellow = FES, red = BES, orange = mechanical storage (without FES)/BES, blue = mechanical storage (without FES); Bubble names: PR = primary response, SR = secondary response, TR = tertiary response, PQ = power quality, TS = time shifting, DCM = demand charge management, T&D = T&D investment deferral, EB&PR = emergency backup & power reliability, BS = black start, SS = seasonal storage.

systematic literature review to determine which EES technology is the most cost-effective for each stationary application.

The findings of this analysis suggest that Li-ion or PHS are viable technologies for most applications, demonstrating their versatility and economic competitiveness. The only exception is primary response, where FES has a comparative advantage for this use case. Looking to the future, seasonal storage is the only application where Li-ion is not expected to be the cheapest technology. Instead, all studies agree that HES will dominate this use case in the upcoming years. These conclusions are tied to specifically defined applications. To provide a universal picture and to increase the usability and value of the results, they were also analyzed in terms of their input parameters to draw conclusions independent of application definitions. The analysis shows that BES, especially Li-ion, is the optimal choice for applications with discharge durations of less than one hour, with the addition of FES for high-frequency cycling scenarios. On the other hand, CAES and, especially PHS, take precedence for applications with durations beyond one hour and power ratings exceeding 10 MW. At the same time, BES remains viable for low-power use cases.

While this thesis has revealed patterns and similarities among the analyzed LCOS studies, it is vital to acknowledge the heterogeneity of methodologies that makes direct comparisons challenging. Differences in assumptions, estimations, and the limited availability of studies -particularly for black start, UPS, and seasonal storage - introduce uncertainties and limitations to the precision and confidence of the conclusions drawn. This makes it crucial to develop norms and guidelines that standardize the calculation of LCOS and promote comparability across studies in the future. In addition, future research efforts should explore the development of more holistic metrics that consider costs, value streams, and environmental and social impacts. Emerging technologies should be included in the evaluation to ensure a comprehensive and up-to-date assessment of the EES landscape. A more quantitative approach to this systematic literature review could increase the reliability of existing conclusions and provide further insights by using a larger sample size to determine correlations between preferred EES technologies and specific input parameters.

From a scientific perspective, this thesis contributes to the existing body of knowledge by providing a comprehensive analysis and comparison of multiple LCOS studies. It highlights the considerable heterogeneity among these studies and provides a clearer understanding of the underlying patterns and similarities. From a practical standpoint, by identifying the most cost-effective EES technologies for different stationary applications, this thesis provides decision-makers, policymakers, and industry stakeholders with valuable information to make informed choices in their storage technology selection. These insights will not only help to reduce costs but also increase the efficiency of storage technology deployment. Furthermore, in the context of the global energy transition, where reliable and efficient storage technologies are critical for integrating intermittent renewable energy sources, this research offers practical guidance for stakeholders to navigate the complexities of energy system transformation.

Deploying EES technologies paves the way for future cost reductions and performance enhancements by enabling economies of scale. Due to the central role of EES in achieving the global energy transition, we cannot wait for more certain times but must invest in these technologies now. This way, we will be taking a far-reaching step toward a greener and more sustainable future

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