Comparative Analysis of Lithium-Ion Batteries and Supercapacitors for Smart Grid Energy Storage

Bachelor's thesis in Electrical Engineering

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Gothenburg, Sweden, 2025

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Foreword

This thesis was completed as a final part of the bachelor's degree in electrical engineering at Chalmers. It is a literature-based study examining energy storage technologies in smart grids. I want to extend my gratitude to my friends and family who have supported me through this writing process. I also want to thank my examiner Thomas Hammarström for his valuable input.

02-06-2025
Che Rangur

Abstract

This thesis presents a comparative analysis of lithium-ion batteries and supercapacitors as energy storage technologies in smart grids. The analysis is based on five parameters: energy density, power density, life cycle, cost and environmental impact. The results reveal that lithium-ion batteries are more appropriate for long-term storage in smart grids. This is due to their exceptionally high energy density and benefits connected to costs. By comparison, supercapacitors offer higher power density, life cycle and lower environmental impact. Making them suitable for smart grid processes like high-frequency peak shaving. A potential hybrid solution that consists of both lithium-ion batteries and supercapacitors were also explored. These hybrid solutions have shown to address a number of the individual concerns faced by both technologies. However, there needs to be more development focusing on the hybrid solution within smart grid infrastructures. While limited by a lack of real-world studies, this thesis offers a valuable framework that could be used in future studies and practical applications in smart grids.

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1. Introduction

Traditional power grids have struggled to integrate renewable energy sources. This challenge led to the development of smart grids. Energy storage has as a result become increasingly important. Two energy storage technologies in particular, lithium-ion batteries and supercapacitors. Both technologies exhibit advantages and limitations, therefore comparing them is the optimal way of determining how they support smart grids.

1.1 Background

Renewable energy sources which seek to replace fossil fuels carry with them their own limitations. Solar and wind energy for example are limited by weather conditions. Energy storage technologies make sure that enough excess energy is stored during times of increased energy demand. This ensures that when renewable sources are not generating energy, stored power could still meet the energy demand.

Smart grids, as an evolution of the traditional power grid, utilize for example automation to enhance energy distribution. There are a variety of technologies which support smart grids, energy storage technologies being one of them. Lithium-ion batteries are able to store a great amount of energy, while supercapacitors deliver energy at a faster rate. Both have their respective trade-offs and their advantages are dependent on the specific application.

A structured comparison of both technologies can serve as a guide to see how each technology performs in smart grids. This provides an outlook to see how suitable the technologies are depending on the needs of the grid.

1.2 Purpose

The purpose of this thesis is to compare lithium-ion batteries and supercapacitors against a number of parameters. It also examines how their characteristics align with the needs of smart grids. The parameters are the following: energy density, power density, life cycle, cost and environmental impact.

1.3 Limitations

This thesis will focus specifically on electric double layer capacitors (EDLC). While other types of supercapacitors like pseudocapacitors will be briefly discussed, they will not be the primary focus. Hybrid energy storage systems that incorporate both electronic components will be explored.

This will be a literature review based entirely on existing literature, utilizing sources from scientific articles, books and reports. No lab experiment or practical implementation will be conducted.

The comparison will be limited to the following key parameters: energy density, power density, cycle life, cost, and environmental impact. While costs and environmental impact will be discussed, the study will not explore policy making or economic modeling. The study does not attempt to propose new designs or to optimize hybrid solutions. The literature review will investigate potential innovations and general trends.

Since there is a lack of literature that compares lithium-ion batteries and supercapacitors in smart grids, a general comparison of the technologies will be conducted. This comparison will be applied to the context of smart grids based on the background section in chapter 2.

1.4 Clarification of research questions

1. How do the energy densities of lithium-ion batteries and supercapacitors compare? How does energy density impact their roles in smart grids?
2. For lithium-ion batteries and supercapacitors, what is the difference in power density? Does this influence their application in smart grids?
3. What is the comparison of life cycles between lithium-ion batteries and supercapacitors? What does this result in when applied in smart grids?
4. Does the cost differ significantly between lithium-ion batteries and supercapacitors? What does this mean for the economic viability of smart grid application?
5. Which of the two technologies has a more negative impact on the environment? What does this mean for their application in smart grids?
6. How could a potential hybrid solution consisting of both technologies overcome the individual limitations in smart grids?

2 Theory/Background

This section will dive into the background of the technologies that are central for this thesis and also discuss the chosen parameters.

2.1 Smart grid

A smart grid is an enhanced power grid that uses a range of digital technologies, from smart meters to AI, to improve electricity generation, transmission and distribution [1]. Smart grids differ from traditional power grids in several ways. Unlike traditional power grids, smart grids use two-way communication with wireless sensors to enable real-time interaction between power suppliers and end users. The wireless sensors allow for the integration of renewable energy and allows end users to adjust their energy consumption based on price signals [2]. Moreover, smart grids are self healing and are adaptable across all sections of its grid [2],[3], meaning smart grids could address faults automatically.

Energy storage in smart grids is used to compensate for the unpredictable nature of renewable energy sources, which are impacted by environmental factors. It stores surplus energy generated during times when there is low demand [4]. This makes energy storage an effective solution for balancing supply and demand in smart grids. Storing energy for long periods of time is critical. But not all energy storage technologies are well-suited for this task. For the long-term storage of energy, one factor becomes critical: energy density. Energy density refers to how much energy could be stored in relation to the size of the technology. Technologies with higher energy density are better options for this purpose.

Pressure is put on smart grids during times of high electricity demand. Energy storage helps ease the strain on the grid during this demand using the process of peak shaving. Peak shaving means releasing stored energy during times of increased demand to prevent damage to the grid. This results in reduced electricity demand and stability for the smart grid [5]. For peak shaving to work efficiently, the stored energy needs to be released fast. In other words, energy storage technologies with a high power density are crucial here. Costs for energy storage technologies have decreased [4], making energy storage an even more appealing solution for smart grids. However, there are variations in costs for different energy storage technologies. For some technologies initial costs could be lower but the maintenance costs, influenced by life cycle, could contribute to higher overall costs. Environmental impact is also a factor to consider. Smart grids aim to reduce the reliance on fossil fuels. This means that the technologies used, need to keep developing to reduce their environmental impact.

Smart grids rely on various energy storage technologies ranging from batteries, supercapacitors, flywheels and pump hydro storage [4]. Lithium-ion batteries and supercapacitors are particularly prevalent, due to their unique characteristics that improve smart grids.

2.2 Lithium-ion batteries

Lithium-ion batteries work based on its main components. The anode, which is negatively charged and made with copper with graphite. The cathode, positively charged and consisting of aluminum and mixed oxides [6]. The battery also consists of a separator, positioned between the anode and cathode and an electrolyte which enables the charge and discharge [6]. When charging, electrons flow from the cathode to the anode. During this process, lithium ions travel through the electrolyte to the anode, ultimately combining with the sent electrons which charge the battery. The discharge process reverses this, lithium ions and electrons are moved back to the cathode from the anode [6]. The battery is considered discharged once the lithium ions are fully absorbed by the cathode.

Lithium-ion batteries are widely used in different applications due to their high energy density. Energy density is measured in watts-hours per kilogram (Wh/kg).The energy density of lithium-ion batteries goes up to 200 Wh/kg, while their life cycle extends to about 3000 cycles with a deep discharge of 80% [7]. This allows the battery to operate until 80% of its capacity is used before discharging, which reduces energy waste. The high energy density of lithium-ion batteries makes them a reliable solution for grid applications.

A number of challenges still persists for lithium-ion batteries. For example, lithium is facing global shortages which makes lithium ion batteries in certain applications too costly [7]. Lithium-ion batteries still produce greenhouse gases, especially during the manufacturing phase [8]. Other challenges include, the need of using less materials while also making lithium ion batteries have higher energy density [8]. Improving safety during production is also an important challenge being tackled.

2.3 Supercapacitors

Supercapacitors are considered a midway alternative energy storage technology between traditional capacitors and batteries [9]. Electric Double-Layer Capacitors or EDLCs are the most commonly used supercapacitors across numerous applications. EDLCs are usually composed of two carbon electrodes, an electrolyte and a separator [10]. The working principle of EDLCs is based on its electrostatic storage rather than electrochemical reactions. As highlighted in [9],[10], negative and positive ions are moved to opposite sides, gathering on the surface of the carbon electrodes. This results in the creation of an electric double layer which enables a long life cycle and a fast charge/discharge.

Supercapacitors’ advantages mainly lie in their particularly high power density and long cycle. Power density is measured in watts per kilogram (W/kg). Their power density typically falls below the 10000 W/kg range [10]. This is beneficial for smart grids, due to the demand for fast response time during fluctuations. The life cycle of supercapacitors is exceptionally high, ranging from hundreds of thousands to millions of cycles [11]. A long life cycle applied to smart grids contributes to reduced costs and supports the transition to renewable energy integration. The fast ability for supercapacitors to charge and discharge is also highly valued.

There are other categories of supercapacitors, such as pseudocapacitors. Pseudocapacitors differ from EDLCs in a number of ways, most notably by using electrochemical reactions for energy storage [9] . The working principle of pseudocapacitors is therefore somewhat similar to batteries [9]. Furthermore, unlike EDLC supercapacitors, pseudocapacitors have a higher energy density [10] but a shorter life cycle [9].

The disadvantage of supercapacitors is for example their low energy density. Supercapacitors are not able to store as much energy as other technologies like lithium-ion batteries. However, their high discharge rate [11] could also be a disadvantage. This refers to the fact that supercapacitors release energy at a fast rate. For a number of applications that require long-term energy storage, supercapacitors face limitations.

2.4 Parameters

The parameters that will be used when comparing the energy storage technologies of this thesis are critical in determining the suitability of energy storage technologies in any application. These parameters in conjunction will determine which technology is more sustainable, efficient and cost effective.

2.4.1 Energy density

Energy density is defined as the quantity of stored energy for a given mass. The measurement is watts-hours per kilogram (Wh/kg). It is an important factor in managing the frequency of energy fluctuations in smart grids. If the energy density is higher this is more easily dealt with.

2.4.2 Power density

Power density indicates the amount of transferred power per unit mass. It is measured in watts per kilogram (W/kg). Power density is a key parameter due to the importance for smart grids to get access to energy with minimum delay, during periods of increased demands. This stabilizes the grid and responds to fluctuations efficiently.

2.4.3 Life cycle

Life cycle refers to the number of times a technology charges and discharges before the performance declines. This parameter is related to reliability in the smart grid. A longer life cycle is more advantageous, because it requires less maintenance and ensures a more consistent long term performance.

2.4.4 Cost

Cost is another crucial factor, as it impacts the scope of the energy storage application. Lower costs makes the technology more attractive for larger scale applications. Initial costs and maintenance cost also factors in when discussing the economics of energy storage technologies.

2.4.5 Environmental impact

The global concern about climate change has started the transition away from fossil fuels. Thus, the environmental impact of energy storage technologies is becoming a bigger focus. Resource extraction and pollution are important factors to examine. The materials being used in the production combined and the recyclability of the technologies are decisive in determining sustainability.

3 Method

This chapter provides the methods, criteria and reasoning used to obtain the sources for this thesis. The limitations in the literature are also discussed.

To obtain the sources used for this thesis, the academic databases IEEE Xplore, ScienceDirect and Google Scholar were used. These databases contain a variety of academic sources, ranging from journals, books, conferences and rapports. The databases were selected to ensure that the information was academic and reliable. To find relevant sources relating to lithium-ion batteries, supercapacitors and smart grids various keywords were used. Phrases such as “lithium-ion batteries energy density”, “smart grids energy storage” , “supercapacitors environmental impact” were written in the databases. The phrases were selected to find specific information corresponding to the sections being written.

Sources were then selected based on their relevance to the thesis, credibility and their publication date. No sources were chosen who were published before the 2000s. Peer-reviewed sources were prioritized to ensure credibility and quality. Despite thorough research, there were still some limitations. There was a lack of literature directly comparing lithium-ion batteries and supercapacitors in smart grids. As a result, a general comparison was made and applied to the needs of smart grids. This limitation required some deducing and assumptions in the result section which could impact the accuracy in the conclusion. There were also some sources containing important information based on their abstract, that were not able to be accessed due to paywalls.

4 Design/Investigations/Solution

This chapter compares lithium-ion batteries and supercapacitors based on the parameters: energy density, power density, cycle life, cost, and environmental impact. The comparison is solely a general comparison of the technologies, meaning it is not based on a specific application. In section 5, the findings from this section will be applied to the specific needs of smart grids, as outlined in section 2.

4.1 Energy density

4.1.1 Energy density in lithium-Ion batteries

Lithium-ion batteries possess a notably high energy density, typically reaching levels of 200 to 300 Wh/kg [12]. This value depends on the chemistry being used. Lithium iron phosphate batteries provide a lower energy density, compared to lithium-ion batteries [12]. There have been developments that seek to further improve energy density. One such example is the application of solid-state lithium ion batteries. Solid-state lithium ion batteries use metal anodes, which could improve the energy density drastically [13]. These batteries differ from traditional lithium ion batteries due to their solid state electrolyte instead of a liquid electrolyte.
The use of high-voltage cathodes is a key factor in increasing energy density [13].

4.1.2 Energy density in supercapacitors

Supercapacitors are used in applications mainly for their high power density and long life cycle. However, they do not possess a high energy density. The usual energy density for supercapacitors is in the 10 Wh/kg range [14]. Two factors contributing to low energy density are capacitance and voltage. The capacitance of supercapacitors is influenced by the pore size which is the diameter of the pores where charges are stored [14]. The energy density is scaled with the square of the voltage [14]. This means that increasing the voltage could increase the amount of energy that could be stored. There has therefore been experimentation with different types of materials and electrolytes. For example, ionic liquid electrolytes reach voltage levels higher than 3 V [14].

4.1.3 Comparison of energy density for lithium-Ion batteries and supercapacitors

In terms of energy density, lithium-ion batteries clearly outperform supercapacitors. Lithium-ion batteries' energy density reaches levels of 200 to 300 Wh/kg [12], while supercapacitors have an energy density of 10 Wh/kg [14]. The tremendous difference in energy density clearly highlights that lithium-ion batteries are more applicable for long term storing of energy. In conclusion, looking purely at energy density, lithium-ion batteries surpass supercapacitors. Supercapacitors rather excel in their fast delivery of energy which will be discussed in the next section on power density

4.2 Power density

4.2.1 Power density in lithium-Ion batteries

Lithium-ion batteries which have an immense energy density, also have a moderate power density output. For example, there have been developments where lithium-ion cells have achieved power density levels up to 3000 W/kg [15]. This was achieved in a light vehicle application. However, it illustrates how lithium-ion batteries could discharge energy at a modest rate. The combination of this power density and energy density results in an efficient solution for a wide array of applications.

4.2.2 Power density in supercapacitors

For supercapacitors, a high power density is considered a defining characteristic. Their electrostatic process enables the fast charge and release of energy. This results in power density values higher than other energy storage technologies. The specified power density of supercapacitors are reported to reach levels under 10000 W/kg [10]. The combination of high power density and a low energy density results in a greater depletion of energy. This is due to the supercapacitor needing to discharge energy that it can not store. This trade off is important when assessing the application of supercapacitors.

4.2.3 Comparison of power density for lithium-Ion batteries and supercapacitors

The power density of the two energy storage technologies differs notably. Lithium-ion batteries possess a moderate power density. There have been documented cases of lithium-ion batteries having a power density of 3000 W/kg [15]. When combining their energy density, moderate power could be delivered over longer periods.

By contrast, supercapacitors exhibit a noticeably higher power density. The value of the power density is typically below 10000 W/kg [10]. Although this comes at the cost of faster energy depletion, due to their low energy density. Lithium-ion batteries could however, deliver energy over drawn-out periods albeit in smaller power outputs.

In summary, supercapacitors, due to their high power density, excel in applications that are in need of rapid energy delivery [16]. Lithium-ion batteries, meanwhile, offer a balance by delivering energy at a slower rate but over a longer duration. Both technologies have their tradeoffs in regards to power density. The choice between lithium-ion batteries or supercapacitors based on power density, must be evaluated based on the specific need of the application. If an application mostly demands frequent discharges of energy, supercapacitors become a better option than lithium-ion batteries.

4.3 Life cycle

4.3.1 Life cycle in lithium-ion batteries

Lithium-ion batteries have a limited life cycle compared to supercapacitors. A cycle refers to the charging and discharging of a battery. The life cycle is counted as 3000 cycles with a 80% discharge [7],[17]. The causes of the degradation which determines the life cycle of the battery are for a multitude of reasons. For example by lithium loss, solid electrolyte interface growth and electrolyte decomposition. This results in an escalated internal resistance inside the battery which reduces the batteries capacity over time [18]. This life cycle is suitable for a wide array of applications. However, when considering large scale applications that require long term stability and cost-effectiveness, the degradation of the battery must be considered.

4.3.2 Life cycle in supercapacitors

What separates supercapacitors most from lithium-ion batteries is their extraordinarily high life cycle. The cycle life could reach as high as 1000000 [11],[19]. This is due to their electrostatic energy storage mechanism which does not experience the same rate of degradation as the electrochemical mechanism of lithium-ion batteries [19]. Despite this high cycle life, supercapacitors are not immune to aging. Performance decline occurs for example due to elevated temperature which exacerbates decomposition processes [19]. As previously mentioned, this decline occurs at much slower rates. This results in a long term suitability across different applications.

4.3.3 Comparison of life cycle for lithium-ion batteries and supercapacitors

The difference in life cycle between lithium-ion batteries and supercapacitors is significant. Lithium-ion batteries, while excelling in some parameters, only have a cycle life of 3000 cycles [7],[17]. This limited cycle life is caused by degradation processes that results in a decreased capacity [18]. Such a limitation complicates the application of lithium-ion batteries in scenarios that require minimal maintenance and long term reliability.

Conversely, supercapacitors have a tremendous life cycle, typically reported to exceed 1000000 cycles [11],[19]. The reason supercapacitors could charge and discharge at this rate without experiencing severe deterioration is because of their electrostatic nature [19]. Supercapictors clearly outperform lithium-ion batteries in this parameter. Making supercapacitors suitable for applications that emphasize constant cycling over longer periods.

4.4 Cost

4.4.1 Cost of Lithium-ion batteries

For lithium-ion batteries, the economic viability depends on the application and the scale of batteries that are being produced [20]. A number of factors influence their costs, including material and life cycle. The manufacturing process alone, which involves a number of complex processes, makes up for 25 % of the total cost for lithium-ion batteries [21].
This brings the importance of production efficiency to the forefront. In recent decades, the price of lithium-ion batteries has decreased. This reduction can be attributed to the upsurge of production volumes and the advancement of energy density [20]. Further cost reduction is a necessity for lithium-ion batteries to be applied on an even larger scale, particularly in grid applications.

4.4.2 Cost of supercapacitors

While supercapacitors are praised for their cycle life and power density, their implementation is limited by high upfront costs. What contributes to this cost is the need for advanced electrode materials and the intricate manufacturing process. Together, this makes up almost 70% of the manufacturing cost [19]. Lithium-ion batteries have had a favorable starting position, due to prior research and a global scalability. Supercapacitors are still considered nascent from a commercial perspective. Due to this, supercapacitors have not seen the same price decrease tied to production that other technologies have [19]. To lower overall costs, research is considering updating the production in scale and process and utilizing alternative, more affordable materials [19].

4.4.3 Comparison of cost for lithium-ion batteries and supercapacitors

Lithium-ion batteries benefit from established production methods, with manufacturing processes contributing about 25% of the total cost [21]. With the improvement of energy density and the increased volume of batteries, has drastically reduced the price [20]. This makes lithium-ion batteries more viable for large scale applications.

In contrast, supercapacitors face higher initial cost due to expensive raw materials and the complex manufacturing process. This accounts for nearly 70% of the total manufacturing cost [19]. Unlike lithium-ion batteries, supercapacitors do not benefit from increased scaling of production which further limits their widespread adoption.

In conclusion, lithium-ion batteries are more economically viable due to their extensive R&D background and cost reduction tied to volume. Supercapacitors could potentially become more economically viable. But cost challenges connected to production and materials need to be addressed.

4.5 Environmental

4.5.1 Environmental impact of lithium-ion batteries

Although lithium-ion batteries are an important factor in the green transition [8], several environmental challenges still persist. The resource extraction of rare metals can lead to the disruption of ecosystems and pollution of local waters and soil [22]. Furthermore, steps such as transport and manufacturing are also associated with greenhouse emissions [8]. To mitigate the environmental impact of these processes to reduce metal extraction, battery recycling is being emphasized. Recycling lithium-ion batteries could recover materials, reduce the reliance on imports and reduce fossil fuels emissions [22],[23]. However, recycling relies on an underdeveloped infrastructure and is in itself energy intensive and hazardous [24]. This leads to most waste ending up in landfills, contributing to environmental harm [24]. Improving the recycling, extraction and manufacture processes is therefore imperative in order to move forward to a more sustainable lithium-ion battery.

4.5.2 Environmental impact of supercapacitors

Supercapacitors are considered to have a generally limited environmental impact [25]. When compared to other energy storage technologies, they exhibit a lower environmental footprint. This is due to a combination of different factors. The long life cycle of supercapacitors results in reduced waste, as fewer replacements are needed [19]. Furthermore, supercapacitors utilize materials such as carbon that are more readily available, recyclable, less hazardous and often evolved from sustainable sources [19]. As a result, supercapacitors produce fewer emissions while also contributing less to ecosystem degradation [19]. Supercapacitors can be hazardous at end of life if not properly managed, and their resource extraction may pose environmental risks [19],[25]. Nonetheless, supercapacitors still represent a relatively environmentally friendly energy storage option.

4.5.3 Comparison of environmental impact for lithium-ion batteries and supercapacitors

Lithium-ion batteries, while a widely adopted technology, have considerable environmental drawbacks. Their resource extraction of precious metals results in pollution and damage to ecosystems [22]. Additionally, the manufacturing process requires massive amounts of energy which causes further emissions [8]. Recycling of lithium-ion batteries is possible, but not widely employed and poses its own environmental and safety risks [24].

Supercapacitors have comparatively lower environmental consequences. They cause less emissions and damage to ecosystems [19]. Their life cycle reduces waste, more abundant, less toxic materials are used and recycling is easier [19]. Supercapacitors still however face challenges related to hazardous end of life disposal [25].

In summary, supercapacitors represent the more environmental option compared to lithium-ion batteries. Further development is needed, but supercapacitors offer less emissions and ecological damage.

4.6 Summary of comparison

To showcase the differences between lithium-ion batteries and supercapacitors, table 4.1 consists of a summary of the results. The discussed parameters are presented, highlighting each technology's advantages and limitations.

Parameters	LIthium-ion batteries	Supercapacitors
Energy density	200-300 Wh/kg	10 Wh/kg
Power density	Reaching up to 3000 W/kg	Reaching up to 10000 W/kg
Life cycle	Under 3000 life cycles	Under 1000000 life cycles
Cost	Seeing an overall decrease due to volume	High costs due to materials and process
Environmental impact	High due to extraction, manufacturing, poor recycling	Lower due to life cycle, recyclability and reduced toxicity

Table 4.1 provides a general summary of the performance of the technologies according to each parameter.

Table 4.1 revealed that lithium-ion batteries outperforms supercapacitors in energy density and costs. While supercapacitors provide a higher life cycle, power density and have a lower impact on the environment. However, choosing one technology over the other is dependent on the application.

5 Results

This chapter applies the comparison from the previous chapter to the context of smart grids. As noted in chapter 1, there is limited literature directly comparing lithium-ion batteries and supercapacitors in smart grids. This analysis is therefore based on the general parameter performances to the operational needs of smart grids mentioned in section 2.2. The purpose is to evaluate how the demands of smart grids could be met by the characteristics of the technologies. There is also a section addressing the potential of a hybrid solution that combines both lithium-ion batteries and supercapacitors.

5.1 Energy density in smart grids

In smart grids, energy density is an especially important consideration. Energy needs to be stored during periods where renewable energy sources cannot generate electricity. In case there is increased demand during these times, stored energy must be available. Therefore, energy storage technologies with higher energy density are more suitable for smart grids.

Lithium-ion batteries outperform supercapacitors in terms of energy density, and are thus more suitable for smart grids in this context. In chapter 4 it was established that lithium-ion batteries have an energy density of upwards of 200 Wh/kg. While the energy density of supercapacitors only reaches 10 Wh/kg. This high energy density allows lithium-ion batteries to store an enormous amount of energy during idle periods of low generation.

For example, solar energy generation is most prevalent during daylight and demands might rise later during the day. Lithium-ion batteries could therefore store a surplus of energy during the day, and release it when needed. High energy density also impacts the reliability of renewable energy within smart grids. This is because with a high energy density, renewable energy sources could still be efficiently used, despite their sporadic generation.

Supercapacitors on the other hand do not perform when it comes to energy density. Their low energy density limits their ability to store a large amount of energy. Something that is significantly important within smart grids. As a result, while excelling in other areas, supercapacitors are less effective than lithium-ion batteries in regards to long term storage in smart grids.

When considering the need for long term storage to offset the unpredictability of renewable energy, lithium-ion batteries offer a clear advantage. Their tremendous energy density balances supply and demand within smart grids. While simultaneously integrating renewable energy efficiently. Supercapacitors do not possess the ability to store energy in this specific application.

5.2 Power density in smart grids

In smart grids, during times of increased demand for electricity, power density becomes especially important. During the process of peak shaving, stored energy must be rapidly discharged so as to not damage the grid. A higher power density is preferred in such situations, because of the need for quick responses. Since the immediacy and scale of the demand could vary, the preference of lithium-ion batteries or supercapacitors is dependent on the energy demand of the smart grid.

The balance between energy and power density is an important consideration. As discussed in chapter 4 ,lithium-ion batteries have a power density of 3000 W/kg. Their high energy and moderate power density make lithium-ion batteries appropriate for gradual energy release over longer periods. In smart grids, peak shaving usually requires the fast release of energy as demand soars. Chapter 4 mentions the power density of supercapacitors almost reaching 10000 W/kg. Their power density and limited energy density makes them better equipped to release quick bursts of energy in short intervals. This is essential for peak shaving, as supercapacitors could manage the demand surge by delivering energy accordingly. Peak shaving does not always involve an intensive short-lived release of energy. In certain scenarios, the peak shaving is more moderate and occurs over an extended period. In such cases, lithium-ion batteries are more suitable.

The choice between lithium-ion batteries or supercapacitors for peak shaving depends on the specific demand of the smart grid. Supercapacitors excel when the peak shaving process requires quick bursts of much energy. Lithium-ion batteries are better suited when the peak shaving occurs over a longer period. The choice is not mutually exclusive. Both technologies are suited for different scenarios in peak shaving. Their distinct characteristics allow both technologies to be used differently based on the demands within the smart grid.

5.3 Life cycle in smart grids

The reliability and long term viability of energy storage technologies in smart grids is influenced by the life cycle of the technologies. Energy storage technologies with longer life cycles could reduce the maintenance costs which determines their long term outlook. With applications that simultaneously require minimal intervention and long term availability, a long life cycle is significant.

Supercapacitors exhibit an enormous life cycle of 1000000 cycles before experiencing any degradation, as mentioned in chapter 4. Smart grids that require frequent charging and discharging, benefit massively if the energy storage technology has a longer life cycle. In applications which involve constant cycling, like peak shaving, supercapacitors' high life cycle is a great advantage. A long life cycle reduces the need for replacements, lowers maintenance costs and contributes to reliability.

In contrast, the life cycle of lithium-ion batteries only reaches 3000 cycles. In smart grids, this could lead to increased maintenance and replacement costs over time. Therefore, supercapacitors are more sustainable for such scenarios. However, this does not mean that lithium-ion batteries are completely unsuitable for smart grids. For example, if a large amount of energy is stored and the discharges occur over a longer period, the limited life cycle is not as critical. In these scenarios, the reduced cycling will not stress the battery as much.

Overall, while an important parameter, the life cycle of energy storage technologies needs to be considered along with other parameters. Supercapacitors offer a longer life cycle than lithium-ion batteries albeit with a lower energy density. This makes them ideal for applications where the smart grid experiences a surge in energy demand over a short period. Lithium-ion batteries have a limited life cycle which comes with consequences. However, their exceptionally high energy density compensates for their limited life cycle in applications with fewer discharges.

5.4 Cost in smart grids

As smart grids continue to be employed in larger scale applications, the economic viability of energy storage technologies becomes more critical. Although costs vary based on location, scale and application, general cost trends as outlined in chapter 4 offer meaningful insight. Factors such as initial investment, maintenance and replacement costs which are connected to life cycle, must be examined. The scalability and long term sustainability of smart grids is connected to the economic parameter.

Chapter 4 outlines that lithium-ion batteries have an established manufacturing process with a long history of research. As a result, lithium-ion batteries underwent cost reductions as the production increased. For large scale applications in smart grids, lithium-ion batteries are an increasingly attractive energy storage technology due to this production upsurge. Combined with their energy density and cost viability, lithium-ion batteries become suitable for large scale employment for long duration storage. However, their limited life cycle may result in increased maintenance and replacement costs.

By contrast, a cost analysis of supercapacitors reveals that supercapacitors face challenges that hinders their large-scale adoption in smart grids. Chapter 4 mentions the high initial costs of supercapacitors connected to materials and manufacturing. There is however potential for long term economic viability in smart grids. Supercapacitors, with their exceptional life cycle, offer long-term value in applications with constant discharges. This is due to the low maintenance and replacement costs.

Currently, lithium-ion batteries offer more economic advantages than supercapacitors in regards to large scale adoption in smart grids. As smart grids evolve, the economic viability of both technologies will depend on the aforementioned cost factors and cost-cutting advancements.

5.5 Environmental impact of smart grids

By integrating renewable energy, smart grids support the sustainability transition. However, this integration is environmentally impacted by the technologies that are utilized by the smart grid. The ecological impact from the energy storage technologies determines the overall environmental impact of the smart grid.

Lithium-ion batteries, as noted in chapter 4, have an ecologically damaging extraction process. The extraction leads to collateral damage such as pollution and the disruption of ecosystems. The manufacturing process also causes further emissions. One core aim of smart grids is the sustainable mass deployment of its system. However, the difficulty of recycling lithium-ion batteries impacts this potential scalability. This is because the underdeveloped recycling infrastructure results in waste and the further reliance on the extraction of materials. Furthermore, the limited life cycle of lithium-ion batteries is associated with additional emissions and waste. This undermines the sustainability of a potential large-scale employment of smart grids. The integration of renewable energy sources could therefore not compensate for the environmental impact of lithium-ion batteries.

Supercapacitors, by contrast, do not cause environmental damage on the same scale. As established in chapter 4, supercapacitors typically utilize materials that are considered abundant and less toxic. Supercapacitors are also easier to recycle, which decreases the reliance on rare materials. With their long life cycle, they omit less emission and decrease waste which aligns with the frequent cycling of peak shaving in smart grids. As smart grids aim to lower its emission and maximize long term sustainability, supercapacitors are an attractive option. The compatibility is especially high for smart grid applications where the low energy density of the supercapacitor is not an obstacle.

Supercapacitors represent the more environmentally friendly option of both technologies. In smart grid applications that put an emphasis on sustainability and frequent cycling, supercapacitors are preferable. The low waste and emissions associated with supercapacitors are suitable with the long-term sustainability goals of smart grids. Lithium-ion batteries, while a highly effective energy storage technology, their harmful ecological impact cannot be disregarded.

5.6 Hybrid solution

A hybrid energy storage solution, refers to a combined use of lithium-ion batteries and supercapacitors. This solution is designed to overcome the limitations and combine the advantages of each technology. While there is limited literature directly reporting on hybrid systems applied to smart grids, their capabilities suggest a strong area for future development.

One experimental hybrid system that combined both technologies saw a number of notable results. The hybrid system combines both technologies through a grid interconnection that also makes use of two inverters and a control system that handles coordination of both technologies

[26]. It stabilized fluctuations, supercapacitors handled peak shaving independently which eased the strain on the batteries [26]. This could eventually extend the limited life cycle of lithium-ion batteries [26]. Additionally, this can also decrease the operational costs and result in less environmental waste. This hybrid energy storage solution addressed the limitations of the individual use of lithium-ion batteries or supercapacitors. Although not explicitly mentioning smart grids, this hybrid solution could effectively decrease costs, expand the life cycle of lithium-ion batteries, alleviate waste and address some of the limitations linked to power and energy density. Because lithium-ion batteries excel in energy density and supercapacitors in power density, by combining them, each technology can complement each other. Supercapacitors handle peak shaving, enabling the lithium-ion batteries to continue storing energy for long-term use. These benefits highlight the potential for hybrid energy storage systems to overcome the limitations faced in smart grids.

6 Conclusions/Discussion

This chapter discusses and analyses the results of the thesis while also going over if the questions of chapter 1 were answered. It also discusses gaps in the literature and suggestions for future research. The sustainability and ethical dimensions are also discussed.

The purpose of this thesis was to investigate how the individual characteristics of lithium-ion batteries and supercapacitors address the needs of smart grids. This was done by looking at a set of parameters and comparing to see how both technologies performed in general against those parameters. The parameters were outlined in chapter 1 as energy density, power density, life cycle, cost and environmental impact. This general comparison was later applied to the operational needs of smart grids. We examine if this thesis effectively compares the two technologies' role in smart grids by investigation if the questions of chapter 1 were answered.

Question 1: How do the energy densities of lithium-ion batteries and supercapacitors compare? How does energy density impact their roles in smart grids?
Chapter 4 established that lithium-ion batteries have an energy density of 200-300 Wh/kg while supercapacitors offer around 10 Wh/kg. When applied to smart grids this means that lithium-ion batteries are more appropriate for long term energy storage. This is especially important due to the inability of renewable energy sources to continuously generate energy. For comparison, supercapacitors with their limited energy density are not able to store large amounts of energy in smart grids. The question is therefore clearly answered lithium-ion batteries outperform supercapacitors in energy density which in the context of smart grids, makes them suitable for long term energy storage.

Question 2: For lithium-ion batteries and supercapacitors, what is the difference in power density? Does this influence their application in smart grids?
Chapter 4 shows that supercapacitors have a power density below 10000 W/kg, while lithium-ion batteries have one of around 3000 W/kg. This makes a big difference in their application in smart grids. For supercapacitors, their high power density makes them appropriate for applications that require rapid delivery of energy. Most notably the process of peak shaving. Lithium-ion batteries, by comparison, could not deliver energy at the same rate due to their power density. This makes lithium-ion batteries more suitable for applications in smart grids that need consistent energy delivered over a longer period. Question 2 is thus answered: the high difference of power density makes supercapacitors more suitable for rapid energy delivery in smart grids, while lithium-ion batteries become more suitable for continued modest energy supply.

Question 3: What is the comparison of life cycles between lithium-ion batteries and supercapacitors? What does this result in when applied in smart grids?
Lithium-ion batteries and supercapacitors differ extensively in life cycle. Chapter 4 posits that lithium-ion batteries have an estimated life cycle of under 3000 cycles. In contrast, supercapacitors are estimated to reach 1000000 cycles. In smart grids, a long life cycle results in a decrease in maintenance costs, environmental waste and the need for constant replacements. Supercapacitors therefore offer these benefits, especially in applications that involve constant charging and discharging, like peak shaving.
Conversely, the short life cycle of lithium-ion batteries results in the aforementioned disadvantages. Question 3 is therefore answered: the comparison of life cycles between

lithium-ion batteries and supercapacitors shows that supercapacitors outperform in this regard. In smart grids, this results in a greater suitability in applications such as peak shaving. It also addresses sustainability and economic concerns by reducing emissions and costs associated with replacements. While the limited life cycle of lithium-ion batteries, presents challenges for applications where frequent cycling is essential.

Question 4:Does the cost differ significantly between lithium-ion batteries and supercapacitors? What does this mean for the economic viability of smart grid application?
Chapter 4 highlights that lithium-ion batteries benefit from cost decreases due to the increase in production. This is juxtaposed with supercapacitors which face high initial costs and no cost decreases due to production surges. Their long life cycle could potentially increase their economic viability in smart grids. Although, their economic restraints hinders their ability to be cost-effective for larger scale smart grids. Lithium-ion batteries are therefore more cost-effective in large scale smart grid applications that emphasize long term storage. However, due to limited quantitative cost data in this thesis, the answer to question 4 is only partially answered. Costs are highly dependent on specific applications and chapter 4 contains a general summary which does not cover every dimension of costs. There is also limited literature for the economics of lithium-ion batteries and supercapacitors in smart grids.

Question 5 :Which of the two technologies has a more negative impact on the environment? What does this mean for their application in smart grids?
In chapter 4, lithium-ion batteries are to have greater environmental consequences than supercapacitors. Lithium-ion batteries have an extractive process that results in a number of ecological consequences, ranging from pollution to the destruction of ecosystems. They also have an overall underdeveloped recycling infrastructure which further adds to their environmental burden. Supercapacitors by comparison, are more environmentally friendly, mainly due to the use of abundant materials, recyclability and their long life cycle. In smart grids, this means that supercapacitors are more sustainable in the long term. Their environmental impact makes them an attractive energy storage option when sustainability is front and center. While still widely used in smart grids, lithium-ion batteries may conflict with the sustainability goals that smart grids are working towards. Their short life cycle also results in frequent replacements which results in further emissions. Therefore, question 5 is answered: lithium-ion batteries have a more negative environmental impact than supercapacitors. This might hinder their wide-scale application in smart grids due to their impact potentially offsetting the sustainable goals of smart grids.

Question 6:How could a potential hybrid solution consisting of both technologies overcome the individual limitations in smart grids?
Chapter 5 showed one specific experimental energy storage solution that consisted of both lithium-ion batteries and supercapacitors. Although not applied specifically to smart grids, the solution showed a number of advantages as opposed to the individual use of the technologies. The short life cycle of lithium-ion could be extended by supercapacitors taking over the peak shaving process independently. This could lower costs and decrease the environmental impacts of replacements and waste. With the combination of both technologies, their individual strengths worked in tandem and more scenarios could be handled efficiently. Question 6 is therefore answered: a hybrid solution overcomes the limitations by combining the high energy density of

lithium-ion batteries and the high power density and life cycle of supercapacitors. However, there needs to be further research to confirm the results in the context of smart grids.

This thesis successfully provided a parameter-based comparison of lithium-ion batteries and supercapacitors in the context of smart grids. The strength of this thesis lies in the clear comparative approach. The environmental dimension was also a valuable aspect of the thesis. As the environmental factor is often overlooked or just briefly mentioned in many technical texts. The most important result was the recognition of the hybrid solution as a potentially viable option for smart grids. Although needing further research and test trials, the hybrid solution could offer the strengths of both technologies while mitigating the limitations found separately. However, there are some limitations in this thesis. This thesis relied mostly on academic literature and could have benefited more from real-world case studies of real applications. The hybrid solution discussed in chapter 5, while potentially promising, needs to be specifically applied in a smart grid context to fully evaluate its efficiency. The lack of literature of lithium-ion batteries and supercapacitors specifically in smart grids impacted the analysis. Many sources discuss the energy storage technologies in isolation, but few explore real life smart grid applications. This meant that some conclusions of chapter 5 were drawn from inference and not direct sources which introduces uncertainty. Additionally, the lack of numerical data in the cost section limited the depth of the analysis of the cost factor.

Despite the limitations, this thesis could be used as a reference for engineers and researchers who are working on smart grid infrastructure. The parameter-based comparison of lithium-ion batteries and supercapacitors could enable engineers to efficiently consider trade-offs when deciding on designs for smart grids.

For future research, there should be focus on real-world smart grid applications that consist of lithium-ion batteries and supercapacitors. Hybrid solutions should be further examined to truly evaluate the potential for wide-scale hybrid employment in smart grids. There should also be more studies focusing on the individual parameters mentioned in this thesis, specifically in smart grids. Additionally, companies should invest more in supercapacitor innovation to make it more competitive in energy storage markets. There should also be investments for further recycling infrastructure for lithium-ion batteries which could make it more sustainable.

This thesis effectively highlights the environmental impact of both technologies. By comparing their individual impact and life cycle, ethical considerations for future energy systems could take place. Recyclability, material extraction and waste accumulation are all important challenges within energy storage technologies. These challenges need to be addressed, to move towards a greener and more sustainable world. The ethical dimensions of resource extraction especially needs to be addressed. This is considering that many of the areas where these materials are extracted are in underdeveloped countries. The resource extraction from these countries usually involves a number of human rights violations. These concerns need to be addressed politically and in engineering as the energy sector continues to evolve.

Use of AI

During the writing process of this thesis, the AI tool ChatGPT was used solely for correcting grammar and for suggesting rephrasing of certain sentences. All suggestions were carefully reviewed and adapted to ensure that the writing was kept original. The content of the thesis is based on academic sources and my own analysis and commentary.

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