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BACHELOR'S THESIS

COMPARATIVE ANALYSIS OF BATTERIES FOR PHOTOVOLTAIC SYSTEMS

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Madrid

September 2023

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Comparative Analysis fo Batteries for Photovoltaics Systems

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ACKNOWLEDGEMENTS

I would like to thank my supervisor Professor Consuelo Alonso Alonso for support, feedback, and guidance on this thesis which helped me not only to complete my BSc degree but also to start a journey of becoming a researcher.

I thankfully acknowledge the support and suggestions that I received from my supervisor at home University - Professor Peter Virtič.

I am deeply grateful to my parents, sisters, and friends for their support, encouragement, and appreciation for my academic achievements.

COMPARATIVE ANALYSIS OF BATTERIES FOR PHOTOVOLTAIC SYSTEMS

Keywords: photovoltaic system, energy storage, analysis, Li-ion battery, solid-state battery.

Abstract

Renewable energies represent unlimited power sources that are significantly reducing greenhouse emissions. The possibilities and advantages of abundantly available solar energy are immense. However, some challenges are preventing solar energy from reaching its full potential regarding its efficiency and energy storage. Therefore, the main focus of this thesis is on electrochemical storage systems. The aim is to compare the currently leading technology – Li-ion battery to the most recent breakthrough in storage systems – the solid-state battery. The thesis includes a comparative analysis of the mentioned technologies, as well as the theoretical part that introduces solar energy and photovoltaic systems with their main components.

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AHP - Analytic hierarchy process
EES - Electrical Energy Storage
PV - Photovoltaic

1 INTRODUCTION

As the energy crisis escalates into the first truly global one, assessing how vulnerable gas supplies could be replaced with other forms of renewable energy becomes critical. This is important not only for financial reasons but also environmental. It is crucial to understand that it has become urgent to invest in renewable energy resources since we have an alarming rate of depletion of the major conventional energy resources. Therefore, the interest in renewable energy is increasing and is expected to have steady growth in the coming years.

Renewable energies are no longer a niche concept but a vital component of our quest for a sustainable future. They represent unlimited power sources since they are constantly being replenished. They do not produce greenhouse emissions or generate waste. One of them is solar energy which is clean and abundantly available.

Climate change is a significant environmental issue that is primarily driven by the burning of fossil fuels such as coal, oil, and natural gas. This results in an increase in global temperatures. The consequences of global temperature rise are numerous and include more frequent and severe heatwaves, melting glaciers, rising sea levels, changing weather patterns, disruptions to ecosystems and biodiversity, and threats to food and water security. Addressing global warming requires reducing greenhouse gas emissions, which involves transitioning to cleaner and more sustainable energy sources – renewables.

Although the energy potential of the Sun is immense, people can consume a part of the energy that is almost 10,000 times smaller than the rate at which solar energy is intercepted by Earth. Furthermore, solar energy faces additional challenges. One of them is harvesting it because of the limited efficiency of the solar cells. Another one is storing it since solar energy production is less predictable and it fluctuates seasonally and even hour to hour, and it cannot be stored long-term. Therefore, in the first part of this research, a solar energy system technology is presented and described, together with all major components, to explain and understand the process of solar energy harvesting and its conversion. The focus is on solar cells as a basic unit of a PV system.

Based on the IRENA report for the year 2021, solar photovoltaic represents 28% of installed renewable energies, which is 866068,76 MW. Solar photovoltaic power capacity is expected to surpass the capacity of natural gas by 2026, as well as the capacity of coal by 2027.

Since the intermittent nature of solar power generation is still a great challenge to its effective utilization, the importance of storing solar energy becomes apparent. Batteries play a crucial role in enabling the efficient and reliable storage of solar energy ensuring its availability even during periods of no sunlight.
Therefore, the second part of this research is dedicated to exploring the significance of batteries in PV systems and the benefits they offer by bridging the gap between supply and demand. The main objective is to compare different battery technologies and conclude which battery type is tzhe most suitable for needs of a PV system, and has the most potential in future of energy storage, by using the AHP method. It is crucial to ensure a steady and reliable power supply making solar energy a more dependable and viable source of electricity. Besides maximizing the self-consumption of solar energy, reducing dependence on the grid and its stabilization, lowering electricity bills, and managing fluctuations in electricity supply and demand, the importance of batteries in solar energy storage goes beyond the technical advantages. Batteries contribute to reducing the overall carbon footprint and enable higher penetration of renewable energy into the grid. Additionally, using batteries in solar energy storage systems minimizes the need for standby power plants typically fueled by fossil fuels, reducing environmental pollution and health risks.

Undoubtedly, the combination of solar power and batteries holds enormous potential to revolutionize the future of energy consumption. By effectively storing excess solar energy and making it available when needed, batteries provide a reliable power supply, independent of external factors. This synergy not only enhances the reliability and resilience of solar power systems but also enables the optimal utilization of renewable energy resources. Finally, the two approaches are combined to form a whole and complete picture of a clean, reliable, and inexhaustible source of energy.

The main goal was to compare the leading present technology – Li-ion batteries and the new possible breakthrough in the storage systems industry – solid-state batteries.

In this context, I believe that this thesis contributes to acknowledging solar power's potential and possibilities to improve its storage system components to reach the highest possible efficiency and deliver the full potential of solar energy.

2 PHOTOVOLTAIC (PV) SYSTEMS

2.1 SOLAR RADIATION

Solar radiation is a general term used for electromagnetic radiation emitted by the Sun that covers a large range of wavelengths. Solar radiation consists of a large number of photons of different energies. To understand the conversion of solar energy, solar radiation is described as a flow of photons as discrete quantum particles that have no mass, but momentum and specific energy.

The total energy of the solar radiation per unit of time at the mean earth-sun distance received on a plane perpendicular to the direction of the sun, outside the earth's atmosphere, is referred to as the solar constant. Its value is adopted as $1367\frac{W}{m^2}$ by the World Radiation Centre. [1]

The amount of solar radiation that reaches a particular place on the earth is not constant. Not only because of the usual daily and yearly variations due to the motion of the sun but also because of the local atmospheric conditions.

The part of sunlight that directly reaches the earth's surface represents the direct component of solar radiation. The other part, the diffuse component, is generated with the scattering of sunlight in the atmosphere. A part of the solar radiation reflected by the earth's surface may also be present in the total solar radiation.

Global radiation is a term used to describe total solar radiation which is made up of direct, diffuse, and reflected components. [3]

2.2 SOLAR ENERGY CONVERSION

Solar energy represents a renewable and inexhaustible energy source harnessed from sunlight. It is one of the fastest-developing technologies among renewables. Therefore, it plays a crucial role in the global market of electricity generation. It can be captured by using various technologies but photovoltaic technology is the most popular.

The solar photovoltaic (PV) system is a technology that was developed to transform the energy from the sun's rays into electricity through solar panels. It represents a sustainable, eco-friendly, low-maintenance technology for generating energy without pollution. [4]

The main components of a PV system are shown in figure 2.1: [5]

1. a solar PV array,
2. a charge controller,
3. a battery bank,
4. an inverter,
5. a power meter, and
6. an electric grid.

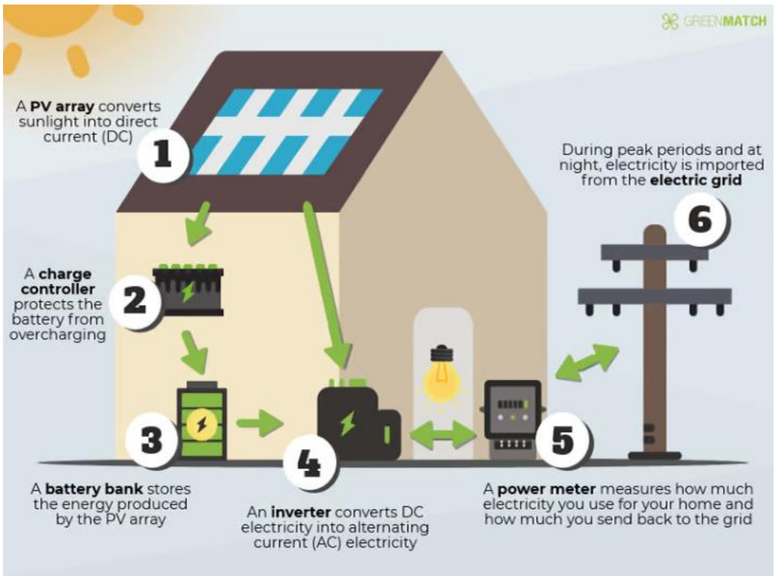


Figure 2.1: Components of a PV system [5]

2.3 SOLAR CELLS

The smallest part that makes up a solar PV array is a solar cell. The solar cell is a PV system's basic, electricity-generating unit. It is also called a photovoltaic cell and it is a device that converts the energy of light into electrical energy through the photovoltaic effect. [6]

The photovoltaic effect is a crucial process for solar energy generation. It is a physical and chemical phenomenon that occurs in solar cells where the light is absorbed and directly converted into electricity. [7]

2.4 SEMICONDUCTORS

Solar cells are composed of semiconductors. Semiconductors are materials that have some properties of a conductor and some of an insulator. They can conduct electricity under certain conditions although not as effectively as conductors and not as poorly as insulators.

Most of the semiconductors are crystals that are typically made of silicon. Silicon has 4 electrons in its valent shell. They tend to share those valent electrons with other atoms nearby. Together, therefore, they form a structure that is called a crystal lattice. Semiconductors are made up of these structures, shown in figure 2.2. [8]

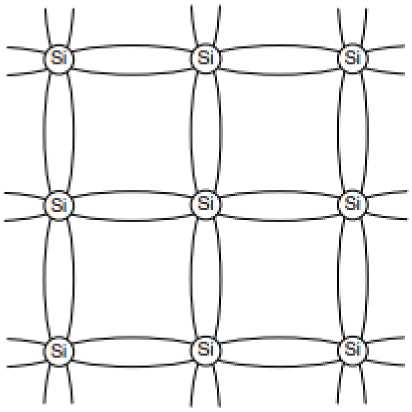


Figure 2.2 : Crystal lattice of Silicon [8]

In their pure form, semiconductors are known as intrinsic semiconductors and have a balanced number of electrons and holes which are vacancies in the electron structure. However, the conductivity of intrinsic semiconductors is relatively low at room temperature. To enhance their conductivity, semiconductors can be doped by intentionally adding impurities to their crystal lattice. This process alters the number of charge carriers in the material, either by introducing additional electrons (n-type doping) or by creating additional holes (p-type doping). The resulting doped semiconductors have improved electrical properties.

The solar cell consists of two different types of semiconductors: P-type and N-type.
P-type is formed when the semiconductor is doped by an element that has only 3 electrons in its valence shell (for example Boron). Because of missing one electron in comparison to silicon, there is a 'hole'. On the other hand, N-type is formed when the semiconductor is doped by an element that has 5 electrons in its valence shell (for example Phosphorus). Since Phosphorus has 5 valence electrons, the fifth electron is excess. It does not have another electron to bond and they move freely through the semiconductor and act as a valence electron in a basic conductor.

By joining these semiconductors together, a P-N junction is formed. In the region of that junction, electrons move to the positive side (P-type) and holes move to the negative side (N-type). This electron moving is the reason for an electric field formation. [8]

2.5 PROCESSES INSIDE A SOLAR CELL

Light particles, photons, are absorbed by the solar cell. The energy that is carried by this photon is transferred to electrons in the semiconducting material in the P-N junction. As a result, electrons jump to a higher energy state – the conduction band. These electrons then move to the N-type side and leave holes in the valence band because they have additional energy from photons. As a result, holes move to the P-type side.

This movement of the electrons creates two charge carriers – an electron-hole pair. This imbalance of charges between the front and the back surface of the cell creates a voltage potential. In this process of electron flow a current is created in the cell. [8]

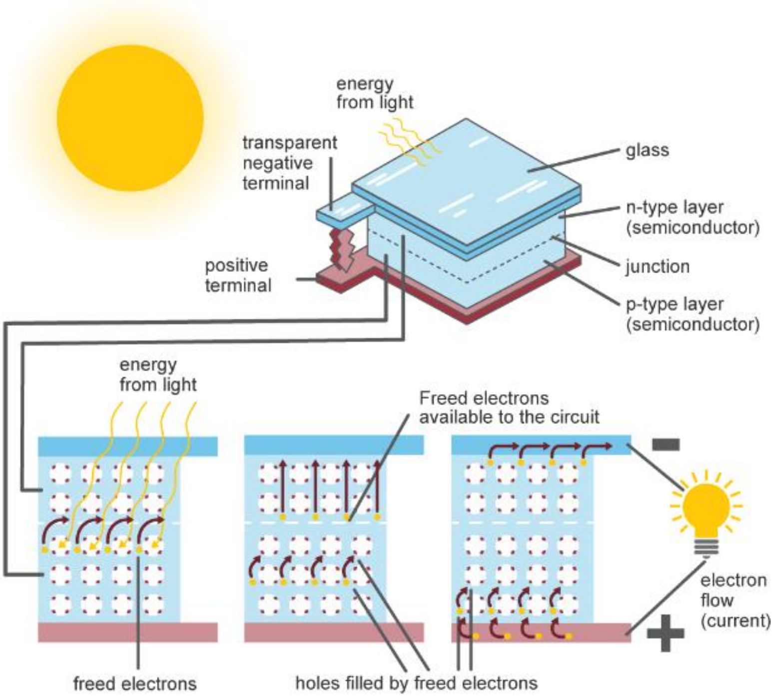


Figure 2.3: Working principles of a solar cell [6]

2.6 TYPES OF SOLAR CELLS

Although there are dozens of solar cells by far, there are 4 main categories that represent generations of solar cells. These photovoltaic cell manufacturing technologies are shown in figure 2.4. [9]

2.6.1 Generations of solar cells

First Generation – Thick Crystalline Films

These cells are the first cells that were produced. They are known for their relatively high efficiency and because of that, they are the most commonly used.

This generation of solar cells includes technologies based on monocrystalline and polycrystalline silicon and gallium arsenide (GaAs). Because of its great semiconductor characteristics in its pure form and since it is one of the most abundant elements on Earth, silicon is the most used material in solar cells.

Second Generation – Thin Film Solar Cells

Besides the development of the first-generation solar cells, this generation is the most remarkable for the development of the thin-film solar cell. They are made by depositing one or more thin layers of PV material onto a substrate. There are several types of thin-film cells but the most common type is the cadmium telluride thin-film solar cell because of its relatively low cost and efficiency. Other thin-film cells are Copper indium gallium selenide (CIGS), Gallium arsenide (GaAs), and Amorphous silicon thin-film cells.

Third Generation – Emerging Technologies

This generation includes new technologies based on more recent chemical compounds. The main goal is to develop the most efficient solar cell which is inexpensive to produce.

Some cells that represent the third generation are nanocrystal solar cells, polymer solar cells, Perovskite cells, etc.

Fourth Generation – Hybrid

The fourth generation is known for the low flexibility or low cost of thin film polymers along with the durability of innovative nanostructures. [6]

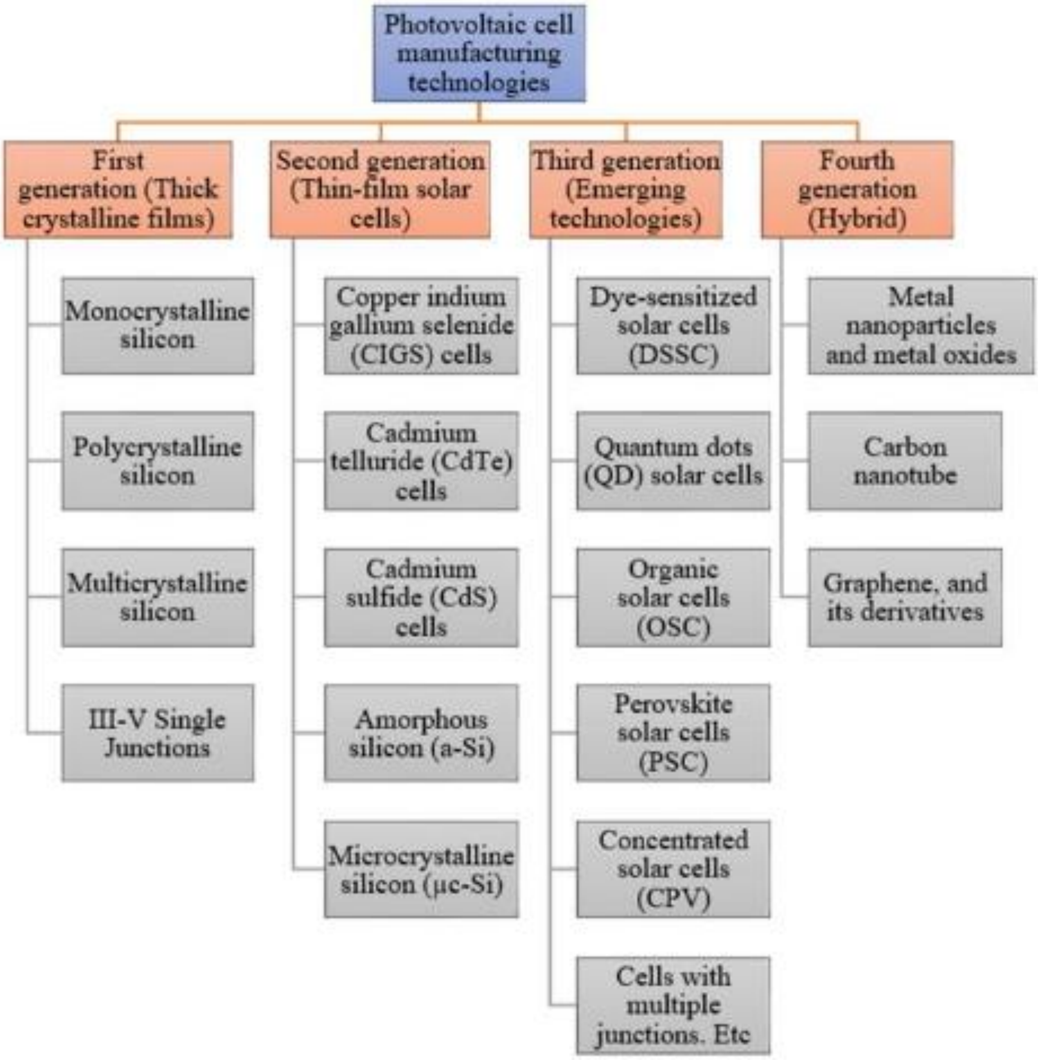


Figure 2.4: Photovoltaic cell manufacturing technologies [9]

2.6.2 The most used solar cells today

Multi-junction Solar Cells: Multi-junction solar cells are the cells that have achieved the highest efficiencies among other cells on the market (beyond 40%). They can capture a broad range of spectrum because they consist of multiple semiconductor layers. They are commonly used in concentrated photovoltaic systems.

Monocrystalline Silicon (Mono-Si): Monocrystalline silicon solar cells have been popular for a very long time based on their high efficiency. They are made from a single crystal structure achieving efficiencies of up to 25%. These cells have a uniform appearance and are the subject of constant research advancements to improve efficiency.

Thin-Film Solar Cells: As their name says, thin-film solar cells consist of very thin layers of different materials deposited on a substrate. The main characteristic of these cells is flexibility but also their lightweight makes them suitable for a broader range of applications. However, their efficiency is overall low in comparison to crystalline silicon cells.

Perovskite Solar Cells: Since Perovskite solar cells are still a new type of solar cell on the market, they are still under development. These cells are made of perovskite materials as the light-harvesting layer. The main advantage is their potential for high efficiency and low manufacturing costs.

Gallium Arsenide (GaAs) Solar Cells: Gallium Arsenide solar cells are a type of multi-junction solar cell reaching efficiencies of around 30%. The most common use of these types of cells is in space (satellites). Because of their high costs, they are rarely used in other applications. [6], [9]

2.7 SOLAR PANELS

When solar cells are mechanically and electrically connected in larger units, they are called solar modules. To generate even greater energy, modules are connected to solar panels.

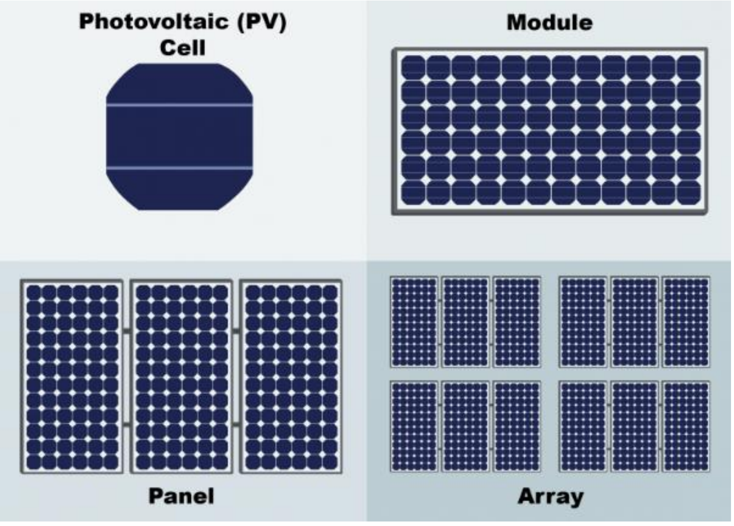


Figure 2.5: PV cell, module, panel and array [10]

2.8 TYPES OF SOLAR PANELS

2.8.1 Monocrystalline

Monocrystalline solar panels are made from a single crystal structure, typically of silicon in the form of high purity. This crystal structure allows better movement of electrons. Therefore, energy conversion is better. Monocrystalline solar panels are popular for their high efficiency, usually between 15% and 22%. Monocrystalline solar panels tend to have higher power output per unit area compared to other types of solar panels making them ideal for installations with limited space. They also perform better in a sense of durability, reliability, and longevity compared to other solar panels (lifespan exceeding 25 years).

Since they offer high efficiency, reliable performance, and a visually appealing appearance, monocrystalline solar panels are widely used in residential, commercial, and utility-scale solar installations. [10]

2.8.2 Polycrystalline

Polycrystalline silicon panels are made from several silicon crystals. They have lower efficiency in comparison to monocrystalline in a range from 13% to 17%. However, the manufacturing process of these panels is cheaper and simpler than that of monocrystalline which gives them a cost advantage and makes them a popular choice in some installations. Polycrystalline silicon panels have a long lifespan (sometimes even more than 30 years). They are designed to ensure durability and reliability to withstand various weather conditions. They are widely deployed in various solar energy projects providing a reliable and efficient source of clean energy. [10]

2.8.3 Thin film

Thin-film solar panels are made of thin semiconductor layers with specific electronic properties deposited onto a substrate.

The most commonly used thin-film materials are:

a. Amorphous Silicon (a-Si): panels made from non-crystalline silicon. They are very flexible and lightweight. They can be deposited onto various substrates.

b. Cadmium Telluride (CdTe): A thin layer of cadmium telluride is used as the semiconductor material. These panels have a high absorption coefficient which allows them to efficiently convert sunlight into electricity without using a lot of material.

c. Copper Indium Gallium Selenide (CIGS): CIGS panels include a thin layer of copper, indium, gallium, and selenium compounds and they are known for a high absorption coefficient.

Thin-film solar panels generally have lower efficiency compared to crystalline silicon panels in a range from 10% to 20%. Since thin-film technology is still under development, there is a lot of potential for efficiency improvement. The greatest advantage of thin-film solar panels in comparison to crystalline silicon panels is the flexibility that allows them to be used in applications to curved surfaces. Also, the manufacturing costs are lower so they are appropriate for large-scale installations. There are ongoing advancements in thin-film technology that aim to broaden their applications in the solar energy industry. [10] [11]

3 ENERGY STORAGE

Energy storage is extremely important since it allows us to maintain and improve the reliability and efficiency of energy while lowering dependence on fossil fuels.

Beyond allowing electricity to be produced and used at different times, storage can provide services to strengthen reliability and resilience. Even though there are the costs of transitioning to renewables and storage technologies, both these costs have dropped rapidly over the past decade with further declines excepted. Also, power grids that invest in renewables and storage are cheaper to operate and they reduce or eliminate the cost of damage from pollution from current systems. Energy storage has a big role to play in our fight against climate change. It can contribute to an affordable clean energy future.

Energy storage devices work on a principle where they are 'charged' when they absorb energy and they 'discharge' when they deliver the stored energy back into the grid.

Energy storage can store additional energy from intermittent renewable sources, such as solar PV until it is required – allowing, therefore, for the integration of additional renewable energy into the system. Increased penetration of variable renewable energy generation makes storage more attractive because this energy generation is intermittent – its output is variable over time and not easily predictable. The use of storage is a great opportunity to cope with intermittency in a way of performing energy arbitrage which is defined as moving electrical energy from low-value to high-value periods. Technologies that can store energy as it is produced and release it just when it is needed so that they support the delicate balance of the power grid. They are especially useful for storing electricity from renewable sources like solar. [11], [12]

Energy storage systems can be organized into 5 storage classes:

1. electrochemical,
2. mechanical,

3. thermal,
4. electrical,
5. chemical.

Classification of energy storage technologies is shown in figure 3.1. [14]

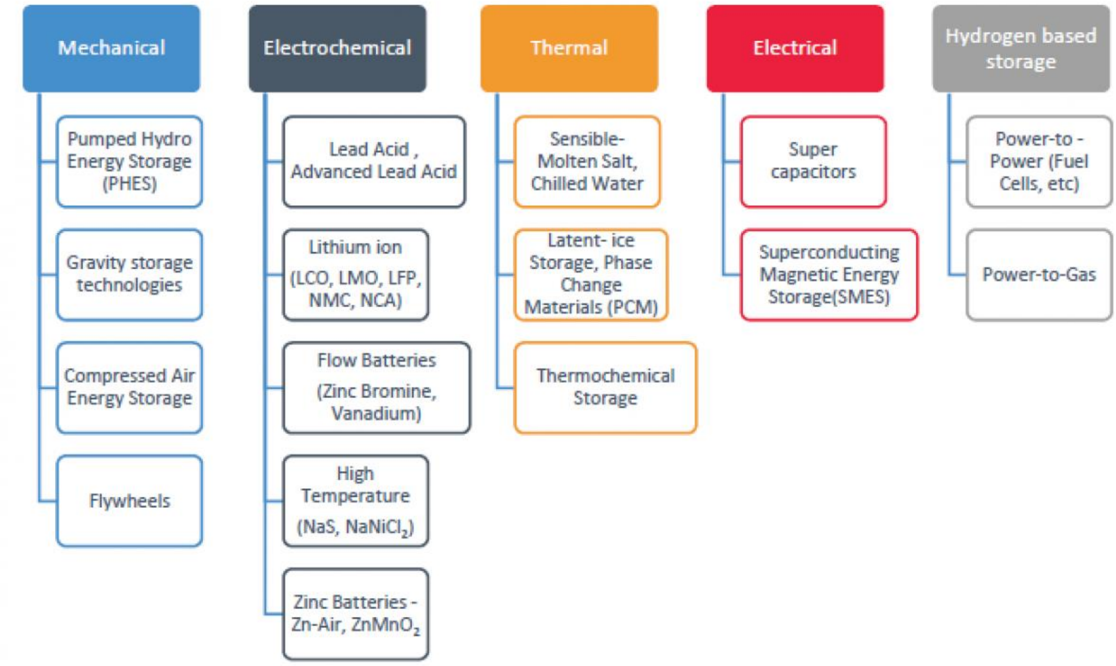


Figure 3.1: Classification of energy storage technologies [14]

3.1 ELECTROCHEMICAL STORAGE SYSTEMS

Electrochemical storage systems are the most traditional of all energy storage devices for power generation. They are based on storing chemical energy that is converted to electrical energy when it is needed. EES systems are usually classified into three categories: batteries, electrochemical capacitors, and fuel cells.

The electrode materials are crucial for EES systems since the electric energy is stored in the chemical bonds of those materials. The energy density, power density, and safety of these devices are mostly dependent on the electrode materials with high electroactivity, high electron/ion conductivity, and high structural/electrochemical stability. [13]

3.2 BATTERIES

A battery is a device that stores energy that can be used by the process of conversion of chemical energy into electric energy. The process of this energy conversion happens through an electrochemical oxidation-reduction reaction. Both oxidation and reduction occur together so this process is often called redox reaction. The key to this reaction is the transfer of electrons from one material to another via an electric circuit. Oxidation occurs at the electrode called the anode, and through this process, a material loses one or more electrons. On the other hand, reduction occurs at the cathode, and in this process, the material gains one or more electrons. These two electrodes are connected through a wire that conducts electrons and measures current or electric potential.

Batteries usually produce electricity through the use of their electrochemical cells.

A cell is a single unit in a battery that produces electricity generating power through a chemical, thermal, or optical process. A typical cell is made of two terminals – electrodes, separated by a barrier that allows electric charge to pass from one electrode to another and an electrolyte. The electricity flow happens because of this exchange of electrons that develops a difference in potential or voltage between two electrodes.

There are two main types of cells:

a. Primary cells – These cells experience permanent change after the chemical reaction between the electrodes and the electrolyte. That means that these batteries can be used only once and they are not rechargeable. They are also often called "dry cells".

b. Secondary cells – Current is generated in the opposite direction of the primary cells. The chemical action occurs in reverse and is effectively restored. Therefore, it allows a battery to be rechargeable. This type of cell is usually called a "wet cell' because it contains a liquid electrolyte. [14], [15]

3.3 PERFORMANCE CHARACTERISTICS OF BATTERIES

3.3.1 Battery capacity

It represents the amount of time that a battery will last expressed in Ampere hours (Ah). That means that the battery with a capacity of 1 Ah will last for one hour operating at one ampere. It is also possible to rate a battery by its energy capacity expressed in watt-hours or kilowatt-hours (kWh). [16]

3.3.2 Energy density

It represents the amount of energy that can be stored in a battery. Energy density can be measured in two ways: per volume or mass. Volumetric energy density is more common and it shows how much energy a battery contains in comparison to its volume. It is typically expressed in watt-hours per liter (Wh/l).

A battery with higher energy density is an advantage because it means it can store the greater amount of energy. Moreover, it means the battery is lighter than one with similar capacity and lower energy density. This characteristic is very important for many applications, not only in portable systems, but also in PV systems because it lowers the costs of their transport to remote locations. [17]

3.3.3 Specific energy

It is also called the gravimetric density and it represents a measure of how much energy a battery contains in comparison to its mass. It can also be said that specific energy illustrates the ability of a battery to hold power.

Specific energy is typically expressed in watt-hours per kilogram (Wh/kg). [16]

3.3.4 Power density

While energy density does not give us information on how quickly energy can be used, we can know this from batteries' power density. It is a measure of power output per unit volume, which means that we can know the rate at which the battery can deliver energy. If a battery has a high power density, it means it can release its energy quickly and recharge quickly. Power density is expressed in watts per liter (W/l) or kilogram (W/kg). [18]

3.3.5 Voltage

One of the fundamental battery characteristics is battery voltage. It is determined by the chemical reactions inside the battery, the concentrations of the battery components, as well as the polarization. It refers to the difference in electrical potential between the positive and negative terminals caused by the potential difference. The greater the potential difference, the greater the voltage of a battery. [16]

3.3.6 Discharge curve

A plot of voltage dependent on the percentage of capacity of a battery is called a discharge curve. It shows whether the voltage remains constant as the battery is used up. The most desirable case is a flat discharge curve which means that the voltage remains stable. [19]

3.3.7 Temperature dependence

The temperature inside a battery is one of the most important factors that influence the battery's performance and lifecycle. In most cases, an optimal operation temperature for batteries is within a temperature range of 25-45 degrees Celsius. Neither very high nor very low temperatures are good for batteries. When the temperature of the battery increases, that means faster chemical reactions inside the battery. Even if this can contribute to a higher performance of a battery, it will decrease the lifecycle of a battery. On the other hand, if the temperature is too low, it means that the battery will need more time and effort to charge and the capacity will be lower. [20]

3.3.8 Cycle life

Battery starts losing the ability to return to its original state with several uses and recharges. The number of charge and discharge cycles before the battery starts losing performance is what we call the lifecycle of a battery. Typically, cycle life ranges from 500 to 1200.

3.3.9 Cost

When we talk about the cost of a battery, it is important to consider the initial cost of a battery, as well as the costs of operating and maintaining it.

3.4 TYPES OF SOLAR BATTERIES

Solar batteries represent a crucial component of a solar system if we want to get the most of the generated energy. To use resources wisely and contribute to the green energy and sustainability movement, every waste of energy would contradict these ideas.

There are many benefits of using solar batteries, such as energy independence, increased self-consumption, backup power, load shifting, grid support, reduction of greenhouse gasses, and many more. [21]

The main types of batteries that are used in PV systems are:

1. Lead-acid,
2. Lithium-ion,
3. Flow batteries, and
4. Nickel Cadmium.

Based on their volumetric and specific energy density, batteries are different in size and weight. Energy density comparison of weight and size is shown in figure 3.2. [22]

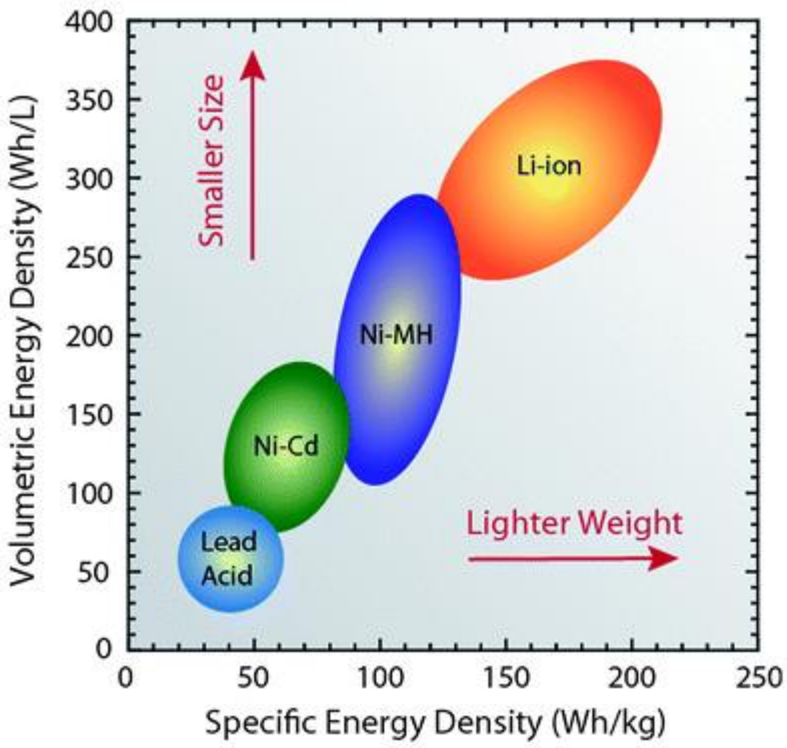


Figure 3.2: Energy density comparison of weight and size [22]

Among these 4 types of solar batteries, lithium-ion batteries are generally considered the most superior lately, and, as such, they have gained the most popularity in the market. This is mainly because of their higher performance and superior characteristics, such as higher energy density, longer cycle life, higher depth of discharge, faster charging, lighter weight, and smaller size of a system in comparison to other battery technologies. [23] However, the energy storage market is very dynamic, and new technologies are always developing. One of them is a solid-state battery which is considered a very promising technology that even offers advantages over current popular lithium-ion batteries.

Given all the reasons above, Li-ion and solid-state batteries act as promising candidates for energy storage in the future. Even though the commercialization and widespread adoption of solid-state batteries are still in the early stages, and they have not yet become a common choice for PV systems, acknowledging its characteristics and advantages in comparison to Li-ion could accelerate deeper research and future development, with possible future application in PV systems.

To be able to perform a comparative analysis of these two types of batteries, it is crucial to get familiar with their structure, working principles, and main characteristics.

3.5 LI-ION BATTERIES

3.5.1 Structure

Li-ion batteries are built of four main components:

1. Cathode – The positive electrode where reduction reactions occur during the discharge or utilization of the battery's stored energy. This part of the Li-ion battery determines the capacity and voltage. Also, it is the electrode in which lithium oxide is inserted and used as an active material.

2. Anode – The negative electrode where oxidation reactions occur during the discharge or utilization of the battery's stored energy. The choice of material is crucial because it impacts batteries' performance characteristics, such as energy density, capacity, cycle life, etc. It is usually made of carbon-based material, such as graphite due to its ability to store and release lithium ions. Also, graphite is known for its structural stability and low electrochemical reactivity. Therefore, it is considered suitable for the anode.

3. Electrolyte – It represents a medium that is the key component in enabling the electrochemical reactions in a battery. The main function of electrolytes is to enable the movement of only lithium ions between the cathode and anode. Therefore, electrolytes need to have high ionic conductivity, low viscosity, and excellent stability in a wide range of temperatures. They are usually a liquid composed of lithium salts dissolved in organic solvents.

4. Separator – A physical barrier that keeps the cathode and anode apart to prevent short circuits. It also prevents the direct flow of electrons and lets only the ions pass through the internal microscopic hole. The separator plays a crucial role in maintaining the battery's safety. It is typically made from a polymer material that performs good chemical and thermal stability, as well as excellent mechanical strength and low electrical conductivity. [24]

Structure of a Lithium-ion battery is shown in figure 3.3. [25]

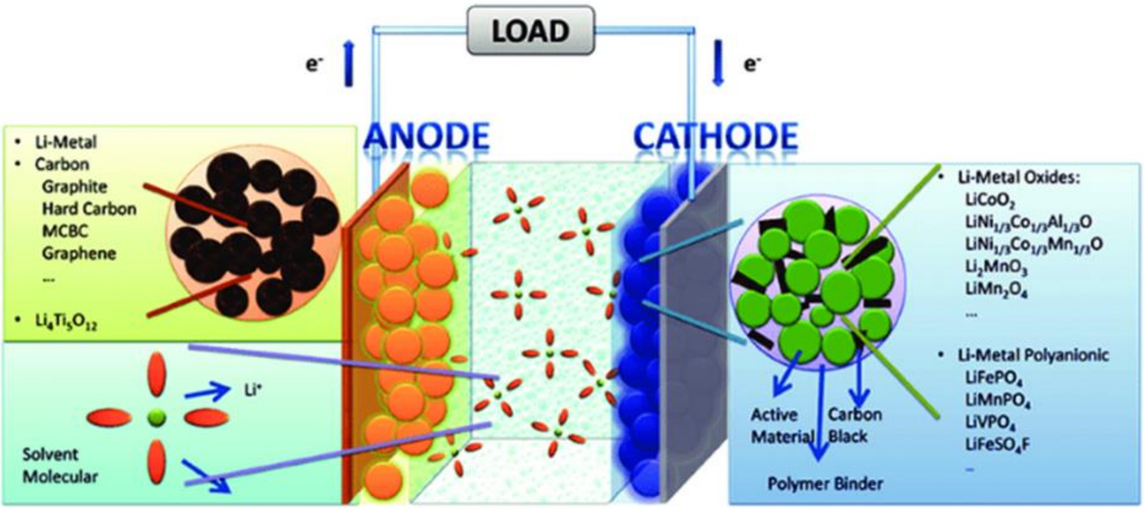


Figure 3.3: Structure of a Li-ion battery [25]

3.5.2 Working principle

Two essential processes for a battery are charge (storing energy) and discharge (using stored energy).

- Charging process

At the beginning of a charging process, the lithium ions are mostly located in the cathode. When a charger is connected to the battery, electrons from the charger flow into the battery through the anode. As electrons enter the anode, lithium ions are extracted from the cathode, and these ions start moving through the electrolyte toward the anode. The electrolyte allows the lithium ions to flow but prevents the flow of electrons. When they reach the anode, lithium-ions are intercalated into the anode while the negatively charged electrons which were released at the beginning of the process flow through the external circuit towards the cathode. In this way, electron flow completes the circuit. Meanwhile, lithium ions from the electrolyte combine with the electrons at the cathode, which causes a reduction reaction allowing the cathode to store the lithium ions. Once a battery reaches the desired state of charge, the process ends and at this point, the battery is considered fully charged with a higher concentration of lithium ions stored in the anode and cathode. [26]

Charging process is shown in figure 3.4. [27]

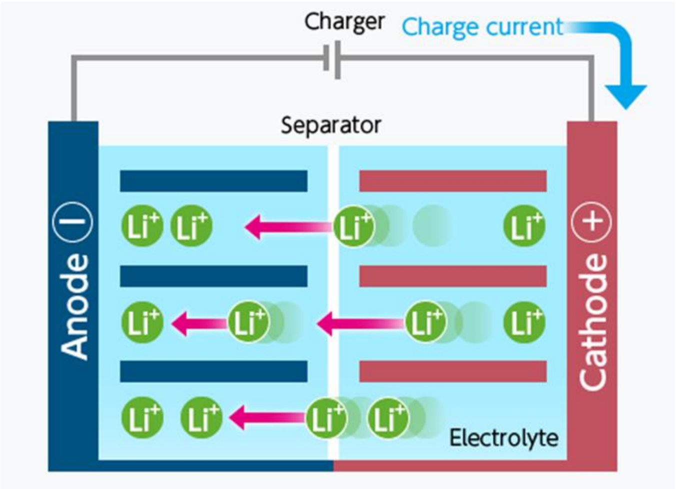


Figure 3.4: Charging process of a Li-ion battery [27]

- Discharging process

Exactly the opposite of a charging process, the discharging process (figure 3.5) involves the release of stored energy. At the beginning of the discharging process, when the circuit is completed with a device connected to the battery, the electrons flow from the anode to the cathode through the external circuit. This electron flow powers the connected device. At the same time, lithium ions are released from the anode. They move through the electrolyte towards the cathode. As these ions reach the cathode, they combine with the electrons that arrive from the external circuit. This causes the reduction reaction at the cathode and it allows the cathode to release stored energy and transfer the lithium ions back to the electrolyte. The point of a discharge process is the conversion of chemical energy stored in the battery to electrical energy which powers the connected device. The discharge process ends when stored energy is depleted and the voltage drops below a certain level. [26]

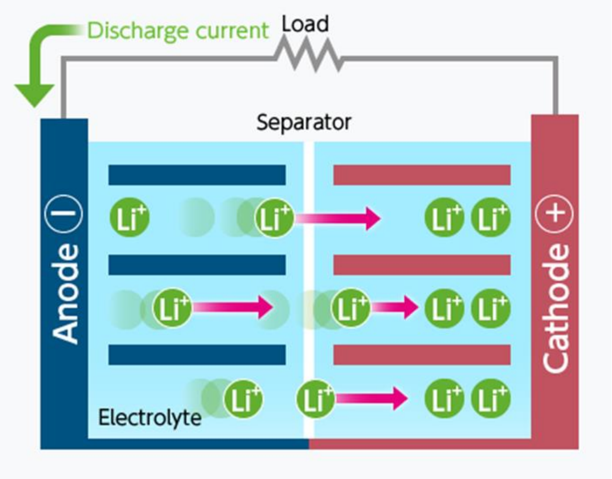


Figure 3.5: Discharging process of a Li-ion battery [27]

3.6 SOLID-STATE BATTERIES

3.6.1 Structure

Solid batteries are built of all solid components:

- A cathode – A positive electrode is usually made of the same materials as a lithium-ion battery.
- An anode – A negative electrode is made of lithium.
- A separator – A central layer of a solid-state battery that acts both as a solid barrier that separates anode and cathode and has a function of the electrolyte. It is usually a ceramic or solid polymer. This part is what makes the main difference between conventional lithium-ion battery that has liquid electrolyte and this new solid-state technology that has solid electrolyte as a medium through which ions move. Its electric insulating properties allow it to work as a mechanical separator between the anode and cathode. A structure of a solid-state battery is shown in figure 3.6. [28]

Figure 3.6: Structure of a solid-state battery [28]

3.6.2 Working principle

Solid-state batteries have almost the same working principles as lithium-ion batteries. Similar conductive materials are used for electrodes, and electrical flow is generated by ions moving through the electrolyte between the cathode and anode. That movement of charged particles produces current. When the battery is charging, the lithium particles move in the direction from the cathode to the anode and through the separator and the anode's electrical contact. It forms a solid layer of pure lithium. This forms an anode made of lithium particles. Therefore, the anode has a smaller volume than the anode in a standard lithium-ion battery that has graphite in its anode.
In the discharge process, particles move in the reverse direction.

The main difference in comparison to conventional lithium-ion batteries is in the solid electrolyte. And because of the solid electrolyte, the separator that separates electrodes and prevents mixing of the liquid is not necessary. The discovery of solid materials that can allow the movement of ions and create a sufficient flow of electricity was crucial for the discovery and development of solid-state storage technology. This solid electrolyte has made it possible to develop batteries with larger capacity and higher output and, at the same time, smaller sizes than lithium-ion batteries. [28], [29]

3.6.3 Performance characteristics

Solid-state batteries are expected to be the future of storage systems and the next generation of secondary batteries. These expectations are based on many advantages they offer in comparison to currently available technologies.

- High energy density

The greatest advantage that solid electrolyte brings to solid-state batteries in comparison to all other battery technologies is the record energy density. The removal of graphite from the anode that is now made of a pure metal allows a huge increase in energy density. Based on the latest research, solid-state batteries have an energy density of 2-3 times higher than current lithium-ion batteries. Higher energy density also means lighter and smaller batteries.

- Can withstand a wide range of temperatures

Since the electrolyte in solid-state batteries is not made of flammable materials as in lithium-ion batteries, there is no concern about use in high-temperature environments. This ability of usage in higher temperatures is especially important in the use of storage systems for PV systems since constant sun exposure could often mean exposure to higher temperatures of its components. While liquid electrolytes tend to suffer at high temperatures, solid electrolyte has even better performance at higher temperatures.

Also, the internal resistance of solid-state batteries does not increase as much as in the case of liquid electrolytes. Therefore, the solid-state battery performance does not drop a lot in case of low temperatures since the solid electrolyte doesn't freeze as easily as the liquid one.

- Fast charging

It is expected that the solid-state batteries will be capable of faster charging since they are more heat resistant and they will not heat up a lot. Based on the latest studies, solid-state batteries are expected to be able to be charged even up to 6 times faster than the other current technologies.

- Long lifespan

The main factor in the longevity of a battery is its electrolyte. Electrolyte deterioration is less present in the case of solid-state batteries. Therefore, it will be possible to extend the lifespan of solid-state batteries further than lithium-ion.

- Safety

With liquid electrolytes being the main concern for safety in lithium-ion batteries, this issue is eliminated when we talk about solid-state batteries. The solid electrolyte is not as volatile and flammable. Therefore, there are almost no risks in cases of external fire. Furthermore, the separator is much thicker and made of a more mechanically resistant material. Therefore, it withstands high temperatures, separates the electrodes more reliably, and prevents short circuits. The thicker separator also impacts the generation of dendrites which is much lower in solid-state batteries. This slows down the deterioration of the cell too. [29]

3.6.4 Main challenges

- Solid electrolyte

Even though solid electrolyte gives huge advantages in solid-state battery performance, there is a challenge for electrodes to maintain close contact with the electrolyte. Furthermore, the perfect material for electrolytes is yet to be found. Research in this field is still in progress and the main goal is to find a solid material with an ideal ionic conductivity.

- Manufacturing processes and cost

Since this technology is very new and still in its early development stages, a manufacturing process will need certain changes and advancements. The production of solid-state batteries will be based on sulfides that are very sensitive to moisture so the production process will require a strict control of moisture. Mass production and manufacturing will be quite complex and expensive in comparison to current storage systems.

- Stability

To keep the battery stable, a cell should be compressed so that the internal layers do not detach. However, the thickness of the anode increases during charging and decreases during discharging. The process is called "cell breathing". Therefore, it is not possible to simply compress and fasten all the layers and keep the cells fixed. [29]

4 COMPARATIVE ANALYSIS BETWEEN LI-ION AND SOLID-STATE BATTERIES

With constant developments and new technologies appearing in the field of energy storage, it is impossible not to notice huge possibilities for improvements and potential breakthroughs in the future of renewables and their storage systems. However, these innovations and advancements can create many challenges in decision-making processes since we are faced with numerous options.

Evaluating options thoroughly, balancing competing priorities, and weighing the pros and cons, as well as assessing their potential outcomes can be overwhelming. Moreover, limited information increases the difficulty of predicting the consequences of our choices. Despite these challenges, gathering information through detailed research, considering priorities, and making a systematic and organized decision-making plan can help a lot in choosing the right option even in complex situations.

4.1 AHP METHOD

To address the problem of choosing the best option by combining qualitative and quantitative aspects, we can use the Analytic Hierarchy Process (AHP). It was created by Thomas Saaty in the 1970s to be able to make a decision and choose the best option from possible alternatives by combining different types of factors and transforming them into a standardized numerical scale.

The AHP consists of a few steps that help us to divide the whole process into smaller parts which will lead us to the final goal. [30]

The most important steps of the AHP method are: [31]

1. building the hierarchy,

2. establishing priorities,
3. synthesizing the ratings, and
4. comparing the alternatives.

4.1.1 Building the AHP hierarchy

1. Define a goal

This is the guiding point through the whole process. In this case, the goal is to choose the battery type for the energy storage system inside of a PV system. The objective of this process is to conclude which technology is better and has higher potential and better performance so that we can focus on it in further research, developments, and investments in the future.

2. Define alternatives

It is important to have a clear list of possible options so that we can compare them against different criteria and priorities based on a final goal. Even though the field of battery technology is rapidly evolving, it is well known that lithium-ion batteries are currently the most commonly used and the best solution for storing solar power. Because of their high energy density, long lifespan, and stability, they have become the leading energy storage solution. For this reason, lithium-ion batteries represent the first alternative in this comparative analysis.

On the other hand, a new technology appeared recently – solid-state batteries. This type of battery is still in the development stage but it shows enormous potential to replace the traditional lithium-ion batteries in the future. Therefore, the second alternative for solar energy storage is a solid-state battery.

3. Define criteria

The best way to define criteria is to determine the challenges that our main goal faces. The main goal is to choose the best option for solar energy storage. Therefore, it is important to consider the main requirements for a reliable, efficient way of storing energy. [31]

Energy density will be the first criterion since it is one of the most important characteristics of a battery. This is especially important for a PV system where we need a battery that can emit power for longer periods because of the fluctuating nature of solar energy. The greater the energy density, the greater the amount of energy that can be stored and used later when there is no solar power generation. Energy density is vital in the world of solar batteries and it has been a leading topic of battery advancement.

Power density is another important criterion for the comparison between two battery types since it refers to how quickly it can discharge its stored energy. Also, high power density allows the battery to recharge quickly.

Thermal stability directly affects the safety of a battery since it has a great influence on the risk of a fire or explosion. When we talk about solar batteries, high thermal stability is crucial since the main reason for battery fires and explosions is because of thermal runaways that are heat-related. Therefore, when choosing a solar battery, it is important to choose a battery with high thermal stability that can withstand high temperatures.

Safety is a criterion that refers both to the safety of people and the environment. Besides flammable components that can cause fires and explosions, batteries contain hazardous substances that can pollute the environment and contaminate land and groundwater, resulting in possible exposure to animals and humans that can seriously impact their health.

The cost of a battery reflects the total cost of battery production, as well as the ongoing costs of operating and maintaining it.

Cycle life refers to the number of charging cycles that a battery can perform before showing degradation so it simply represents the longevity of a battery. The greater the cycle life, the less often we would need to replace batteries. The cycle life of a battery is a very important criterion that should be considered when planning the investment in a PV system. [16]

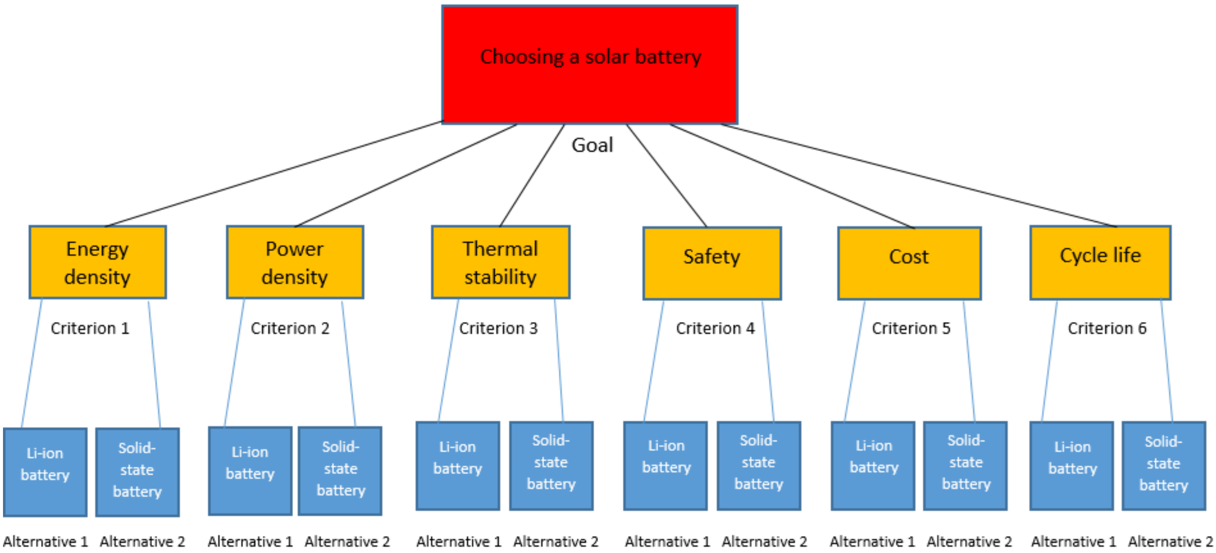


Figure 4.1: The AHP hierarchy [Own source]

4.1.2 Establishing priorities

Once the comparison criteria are defined, it is necessary to determine criteria preferences using paired comparison. Not all criteria are equally important, so each of them has to be rated based on preferences. Since the goal of this comparison method is to find tne best option for solar battery, it is important to weigh criteria based on their importance. Even though each one of them has a great impact on the overall result, this comparison will be rather focused on the technical part than the economical one. The end goal is to highlight the technical potential that lies in the performance of solid-state batteries. Therefore, these reasons allow us to prioritize all other performance characteristics over cost, for example. That does not mean that cost is not an important part of the overall picture. It just means that the financial aspect is not the focus of this comparison. Moreover, the cost of batteries has rapidly been decreasing for the last few years and is expected to decrease in the future as well so this criterion is not taken as vital in the process of choosing the best option for energy storage.

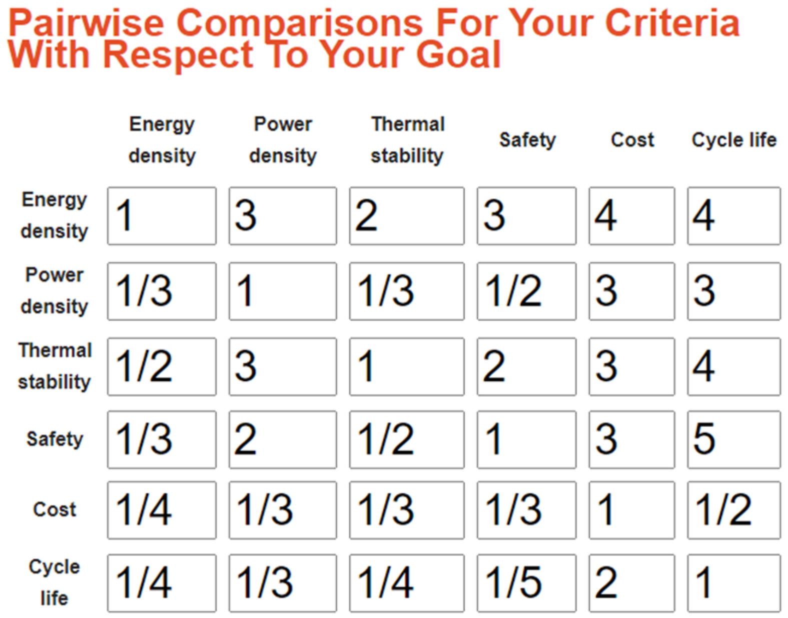
Similarly, cycle life is more related to the economic aspect. If a battery has a shorter cycle life, it means it will lose its performance sooner, and the battery will have to be replaced with a new one.

On the other hand, we have energy density as the most important criterion weighed as 2, 3, or even 4 times more important than other characteristics. The reason for this is the fact that the amount of energy stored in the battery is crucial when we talk about PV systems. Since the main disadvantage of solar energy is its fluctuating nature, it is important to have a storage system that will be able to support a PV system in a way that stores a greater amount of energy that can be used later when it is needed and when generation of energy is not possible. Energy density also impacts the weight of a battery. If energy density is higher, therefore, the battery will be lighter in mass, which is also preferred especially if we talk about remote locations where the transportation and installation of batteries are more complicated. [17]

Thermal stability is ranked as the most important criterion right after energy density. Since it represents the ability of a battery to resist breaking down under heat stress, high thermal stability is crucial, especially in the case of solar batteries. It directly impacts the battery performance as well as the risk of safety hazards.

Therefore, the next criterion is safety, weighted very similar to a thermal stability one. Lastly, there is a power density. Even though it gives us information about how fast the energy can be delivered, this characteristic is not critical in photovoltaic systems. [20]

Pairwise comparison is shown in figure 4.2.



Pairwise Comparisons For Your Criteria With Respect To Your Goal

	Energy density	Power density	Thermal stability	Safety	Cost	Cycle life
Energy density	1	3	2	3	4	4
Power density	1/3	1	1/3	1/2	3	3
Thermal stability	1/2	3	1	2	3	4
Safety	1/3	2	1/2	1	3	5
Cost	1/4	1/3	1/3	1/3	1	1/2
Cycle life	1/4	1/3	1/4	1/5	2	1

Figure 4.2: Pairwise comparison of chosen criteria [Own source]

4.1.3 Synthesizing the ratings

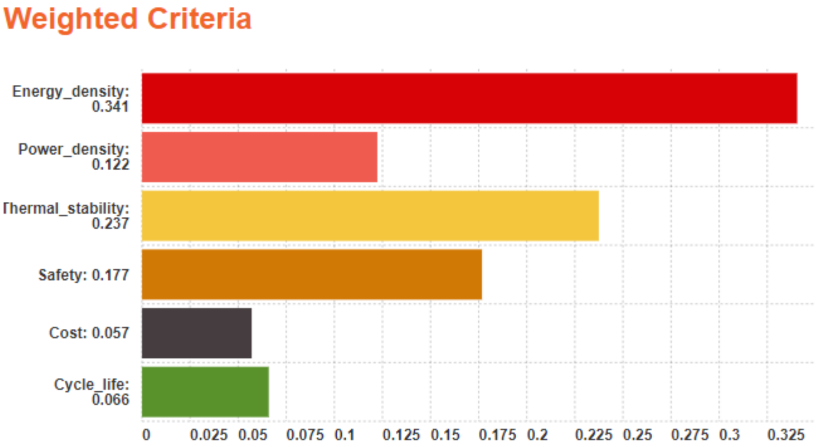
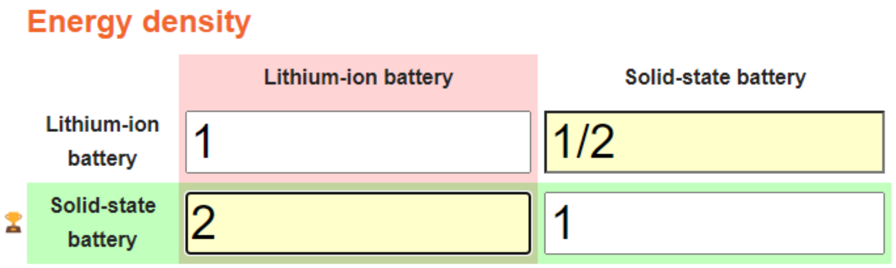


Figure 4.3: Weighted criteria [Own source]

4.1.4 Comparing the alternatives

In this part of the comparison process, each criterion is compared between given alternatives.

When we analyze the energy density, lithium-ion batteries are close to reaching the limits in the technology advancements, especially because of the liquid electrolyte solution. On the other hand, there are solid-state batteries that have solid electrolytes instead of liquid ones. Thus, these batteries can be smaller, more compact, and reach energy density 2-3 times higher than conventional lithium-ion batteries. Energy density comparison is shown in figure 4.4. [32]

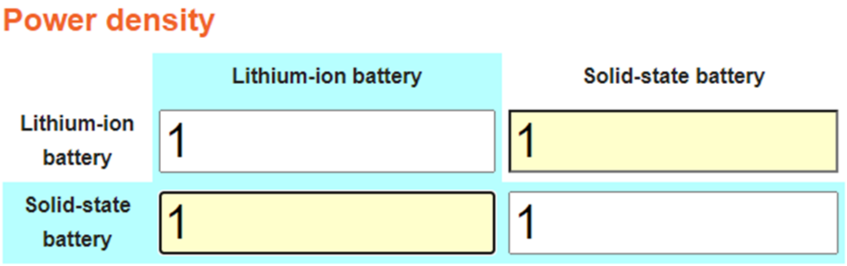


Energy density

	Lithium-ion battery	Solid-state battery
Lithium-ion battery	1	1/2
Solid-state battery	2	1

Figure 4.4: Energy density comparison [32]

For a solar battery, power density is a bit less important than energy density and this criteria still has not been researched enough. It is assumed that the solid-state batteries will have a similar power density as the current lithium-ion batteries. Therefore, these criteria will not affect the final goal based on current knowledge, which is shown in figure 4.5. [33]

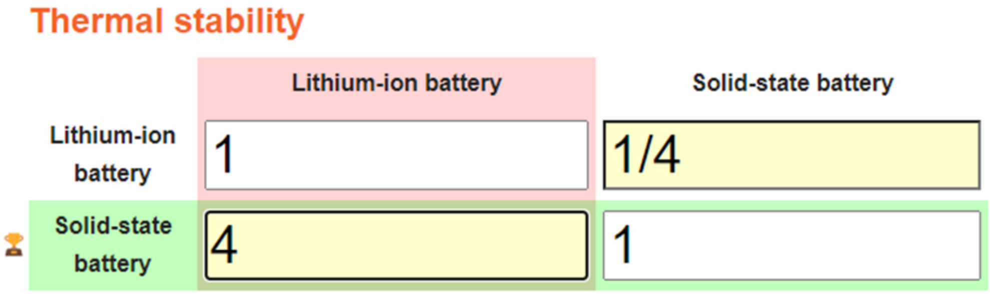


Power density

	Lithium-ion battery	Solid-state battery
Lithium-ion battery	1	1
Solid-state battery	1	1

Figure 4.5: Power density comparison [33]

Thermal stability is critically dependent on the electrolyte type. Since lithium-ion batteries have liquid electrolyte that is sensitive to high temperatures, they can cause a thermal runaway and safety hazards. On the other hand, solid-state batteries are less prone to overheating and therefore cannot easily cause fire. In recent studies, it was discovered that the newly developed solid-state electrolytes have thermal stability up to 4 times higher than standard liquid electrolytes used in lithium-ion batteries, shown in figure 4.6. [34]



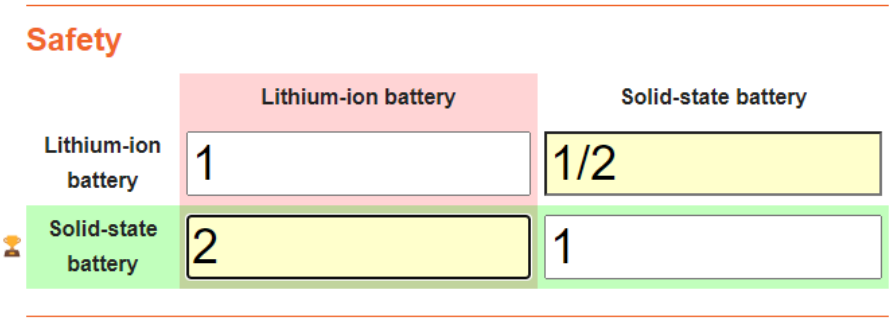
Thermal stability

	Lithium-ion battery	Solid-state battery
Lithium-ion battery	1	1/4
Solid-state battery	4	1

Figure 4.6: Thermal stability comparison [34]

To ensure that the PV system operates normally, all the parts of the system have to function properly and be safe for use. Battery safety issues are directly related to this topic. It is essential to ensure the mechanical safety of solar batteries. That means that the materials used in construction have to be high-strength and include sealing devices to protect the battery from water penetration. Another great concern regarding battery safety is protection from overheating which leads to fire, explosion, and leakage.

Having no flammable liquid electrolyte, solid-state batteries are considered way safer than conventional lithium-ion batteries. In the case of external heating, a solid-state battery produced no heat while a battery with a small amount of liquid produced almost 5 times more heat. Solid-state batteries are unlikely to break because of the firm electrolyte if we consider mechanical failures. Based on these considered scenarios, a solid-state battery is marked as at least twice safer than a conventional lithium-ion battery, shown in figure 4.7. [34]

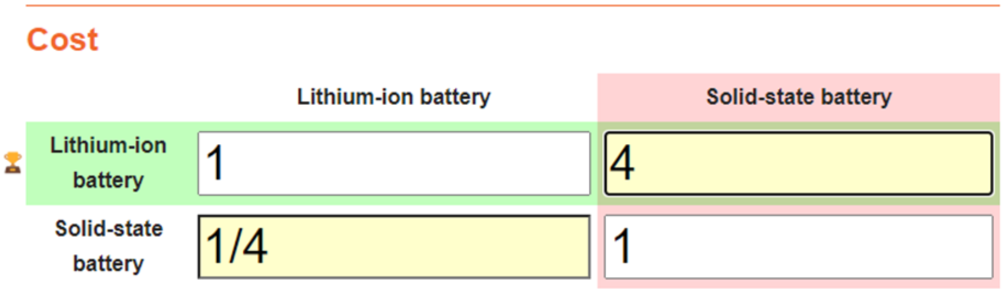


Safety

	Lithium-ion battery	Solid-state battery
Lithium-ion battery	1	1/2
🏆 Solid-state battery	2	1

Figure 4.7: Safety comparison [34]

With great improvements and rising popularity on the market, the cost of lithium-ion batteries has significantly reduced in the last few years. On the other hand, solid-state batteries are still in development and there are many concerns related to high production costs. Solid-state systems are estimated to have initial cost higher than lithium-ion batteries, at least 4 times higher, as shown in figure 4.8. [35]

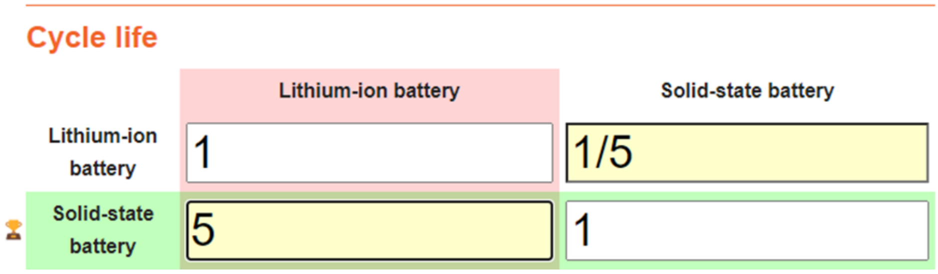


Cost

	Lithium-ion battery	Solid-state battery
🏆 Lithium-ion battery	1	4
Solid-state battery	1/4	1

Figure 4.8: Cost comparison [35]

Solid-state batteries are expected to be able to maintain 90% of their capacity after 5000 cycles while lithium-ion batteries start to degrade after 1000 cycles. This is due to electrode corrosion in the liquid electrolyte caused by chemicals inside a lithium-ion battery. That advantage will allow solid-state batteries to be recharged 5 to 7 times more than conventional lithium-ion batteries, shown in figure 4.9. [36]



Cycle life

	Lithium-ion battery	Solid-state battery
Lithium-ion battery	1	1/5
🏆 Solid-state battery	5	1

Figure 4.9: Cycle life comparison [36]

4.1.5 Scored options

Taking into account all the criteria that determine the efficiency and reliability of the energy storage, the final results are calculated based on the input data and explanations that support it. Using the AHP software tool, scored options are shown in percentage values for each criterion, as well as in total results. From the chart below (figure 4.10), it is visible that the solid-state battery shows better performance in most of the weighted criteria. The current knowledge we have about solid-state batteries is not enough to assert with certainty that they will completely replace lithium-ion batteries but we can say that based on these estimated performances, the solid-state technology is very likely to gain its opportunity to be researched more in-depth. Not only it could be used in PV systems but it shows incredible opportunities for the electric vehicle industry. Being that lightweight and having high energy density, the most crucial obstacles that current batteries for electric vehicles face could be solved. Growing interest and possible application in many different areas are good signs for future development and investment in further research in solid-state technology.

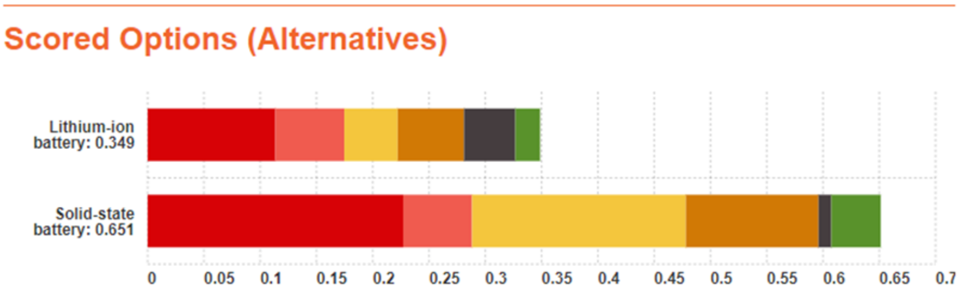


Figure 4.10: Scored options chart [Own source]

5 CONCLUSION

The goal of the thesis was to compare batteries suitable for a photovoltaic system, taking into account their main performance characteristics, as well as ranking them based on their impact on the efficiency of a PV system.

The thesis describes solar energy as a crucial renewable energy source, as well as the different types of PV system's main components. Besides a brief description of solar cells and solar panels, the main focus is on energy storage systems. A comparative analysis between battery types is carried out based on their performance characteristics that have the biggest impact and contribution to the efficiency and safety of a PV system.

Having many advantages over other battery technologies, the use and interest in Li-ion batteries have rapidly grown over recent years. They are considered the most popular batteries on the market today. Furthermore, Li-ion batteries are one of the most researched and improved storage technologies by far. There is a wide variety of Li-ion battery cells. Some of their forms are ideal for solar batteries because of their high energy density and lighter weight compared to other storage technologies.

However, Li-ion technology is reaching its limits regarding energy density and specific energy. Meanwhile, solid-state battery technology appeared and is seen as a possible future of energy storage systems.

Based on the comparative analysis between these two technologies, it is obvious that solid-state technology offers many possibilities for improvement and the potential to outgrow the current leader – Li-ion. Of course, it takes far more investments for deeper research and development.

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