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Review

The Energy Storage Technology Revolution to Achieve Climate Neutrality

Ioana-Cristina Badea [1,†], Beatrice-Adriana Șerban [1,*,†], Ioana Anasiei [1], Dumitru Mitrică [1], Mihai Tudor Olaru [1], Andrey Rabin [2] and Mariana Ciurdaș [3]

[1] National R&D Institute for Non-Ferrous and Rare Metals, 102 Biruinței, 077145 Pantelimon, Romania; cristina.banica@imnr.ro (I.-C.B.); ianasiei@imnr.ro (I.A.); dmitrica@imnr.ro (D.M.); o.mihai@imnr.ro (M.T.O.)
[2] Materials Engineering Department, Ben-Gurion University of the Negev, David Ben Gurion Blvd 1, Beer-Sheva 84105, Israel; andreyra@post.bgu.ac.il
[3] Faculty of Materials Science and Engineering, National University of Science and Technology Politehnica Bucharest, 313 Splaiul Independentei, 060042 Bucharest, Romania; m.ciurdas@upb.ro
* Correspondence: beatrice.carlan@imnr.ro
† These authors contributed equally to this work.

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Abstract: The intensive exploitation and usage of fossil fuels has led to serious environmental consequences, including soil, water, and air pollution and climate changes, and it has compromised the natural resources available for future generations. In this context, identifying new energy storage technologies can be considered a sustainable solution to these problems, with potential long-term effects. In this work, were analyzed different alternatives that can be suitable for replacing non-renewable sources, where hydrogen, wave, wind, or solar energies were considered. Although they have numerous advantages in terms of usage and substantially reducing the environmental impact, this paper is focused on lithium-ion batteries, whose high performance and safety during operation have made them attractive for a wide range of applications. The study of potential replacement technologies and the technical requirements for the main materials used is the starting point in reducing the environmental footprint, without affecting the technical capabilities, followed by the transition toward economic circularity and climate neutrality.

Keywords: fossil fuels; energy storage technologies; material capabilities; environmental footprint; climate neutrality

1. Introduction

The transport industry is considered one of the main global consumers of natural resources, as well as the largest producer of greenhouse gas emissions, the effects of which contribute to accelerating the global warming phenomenon [1]. Currently, reducing automotive usage cannot happen suddenly in society; therefore, identifying alternatives for replacing non-renewable sources and decreasing generated pollutant emissions are promising future perspectives [2,3]. To stimulate the progress and transition toward the circular economy, the cost of developed technology is a significant variable, with a high impact on increasing the quality of life [4–6]. In addition, these alternatives should improve energy efficiency, increase energy conservation potential, encourage accessibility on a large scale, and decrease the environmental footprint of the entire process, from the design stage to recycling [7].

The implementation of these measures is necessary since climate changes are considered a significant threat to human evolution in the future. Therefore, any action that results in a reduction in anthropogenic impacts should be considered, optimized, and implemented [8–10].

Scientists are constantly looking to develop energy systems [11,12] that harness energy from renewable and sustainable sources, such as solar, wind, wave, or geothermal energy.

Solar and wind energy are generally dependent on weather conditions, wave energy is harnessed from the oceans, and geothermal energy from rocks and fluids comes from the earth's shell [13–15]. Therefore, it can be stated that these energy sources are location-dependent and difficult to store and transport.

For these reasons, a growing interest in hydrogen-based technologies has appeared in recent years. Hydrogen can be considered a renewable and abundant energy source and a "clean" fuel, which releases only water vapor into the environment during the electrochemical oxidation involved in the combustion process [16,17]. Moreover, hydrogen can be stored in portable and transportable systems, being an alternative energy source for motor vehicles. Hydrogen storage materials possess ecological and cost advantages, but the main bottlenecks are the high storage pressure, low volume concentration, and difficulties related to charging/discharging kinetics [18].

Another potential candidate for fossil fuel replacement is lithium-ion batteries, which stimulate the transition to electric vehicles [3,19]. This process involves numerous advantages but also has challenges that should be overcome. Even if lithium-ion battery technology has a fast evolution over time, the energy density has a lower value compared with conventional fossil fuels [20–22]. For commonly used vehicles, multiple solutions have been implemented with the main purpose of reducing total weight or increasing autonomy. But problems arise in the case of heavy vehicles, whose battery systems are too heavy to be considered practical [23].

The replacement of fossil fuels with alternative technologies faces some constraints. Owing to the increased performance of fossil fuels, it is necessary to promote an industrial form of sustainable development [24,25]. The use of fossil fuels in the transport industry has a negative ecological impact due to the release of greenhouse gases into the atmosphere [26]. This process determines significant changes in the earth's energy and radiation balance, leading to an increase in the quantity of heat absorbed in the lower atmosphere. Therefore, identifying and developing new technologies and materials with energy storage potential is essential to reducing the industrial environmental footprint and, implicitly, slowing down the global warming phenomenon.

2. Classification of Energy Storage Technologies

2.1. Energy Storage System Evolution

The first reference to the *fuel cell* concept appeared in 1839, which represents the starting point for energy storage system development. British physicist Sir William Grove used the catalysis process to obtain electricity and water by mixing hydrogen and oxygen as fuels. This type of fuel cell operates with similar materials to today's phosphoric acid fuel cell [27].

The ancestor of the rechargeable battery is the *lead-acid battery*. This early form of a rechargeable battery was developed in 1859 by the French physician Gaston Planté. For his initial model, Planté used two lead sheets separated with rubber strips and rolled into a spiral. The first application of this battery consisted of powering the lights in train carriages when stopped at a station [28].

Another step in the energy storage system evolution was the development of the flywheel, also known as the "mechanical battery". This technology, used for energy storage in the form of rotational kinetic energy, began during the Industrial Revolution period. *Flywheel energy storage* was implemented in the military area starting in 1883 [29].

The *nickel-cadmium battery*, invented by Waldemar Jungner in 1899, consists of an anode made from a mixture of cadmium and iron, a cathode composed of nickel hydroxide ($Ni(OH)_2$), and an alkaline electrolyte composed of aqueous KOH [30,31].

In 1907, Italy and Switzerland became the first countries to utilize pumped storage. This hydroelectric energy storage is based on water movement between two reservoirs that can generate power. This kind of system can both generate and store energy, so it can be stated that it is acting like an extremely big battery [32,33].

Sodium sulfur batteries were developed by Ford Motor Company in 1960 to power the new models of electric cars. This type of energy storage uses liquid sodium and liquid sulfur electrodes [34,35].

Superconducting magnetic energy storage, invented by M. Ferrier in 1970, uses superconducting coils to store magnetic energy [36].

The first *borehole thermal energy storage* (BTES) sites were developed in a xylem factory located in Sweden. This type of technology involves energy storage with a solid storage medium (rocks and sands) [37,38].

Compressed-air energy storage (CAES) technology was implemented for the first time in a power plant located in Huntorf, Germany, in 1978. Stored energy can be produced by coal and nuclear power plants. There are several systems, including the development of small-scale compressed air energy storage [39].

The *supercapacitor*, also known as the ultracapacitor, was developed by the Pinnacle Research Institute (PRI) in 1982. Its first applicability was in the military field [40].

One year later, in 1983, the researchers M. Skyllas-Kazacos and coworkers laid the foundation for the development of a *vanadium redox flow battery* at the University of New South Wales, Australia [41].

Also in 1983, R. Remick et al. were the first to perform scientific research on the bromine-polysulfide flow battery, which is a type of rechargeable electric battery [42].

In 1991, Sony and Asahi Kasei assembled the first *lithium-ion battery* [43].

In 2007, the *paper battery*, a different type of electric battery, with cellulose as a major constituent, was created by a group of students from Rensselaer Polytechnic Institute in Troy, New York [44].

2.2. Energy Storage Technology Grading

Energy storage technologies are classified into a variety of systems, which can be divided into five broad categories: mechanical, electrochemical (or batteries), thermal, electrical, and chemical storage technologies (Figure 1).

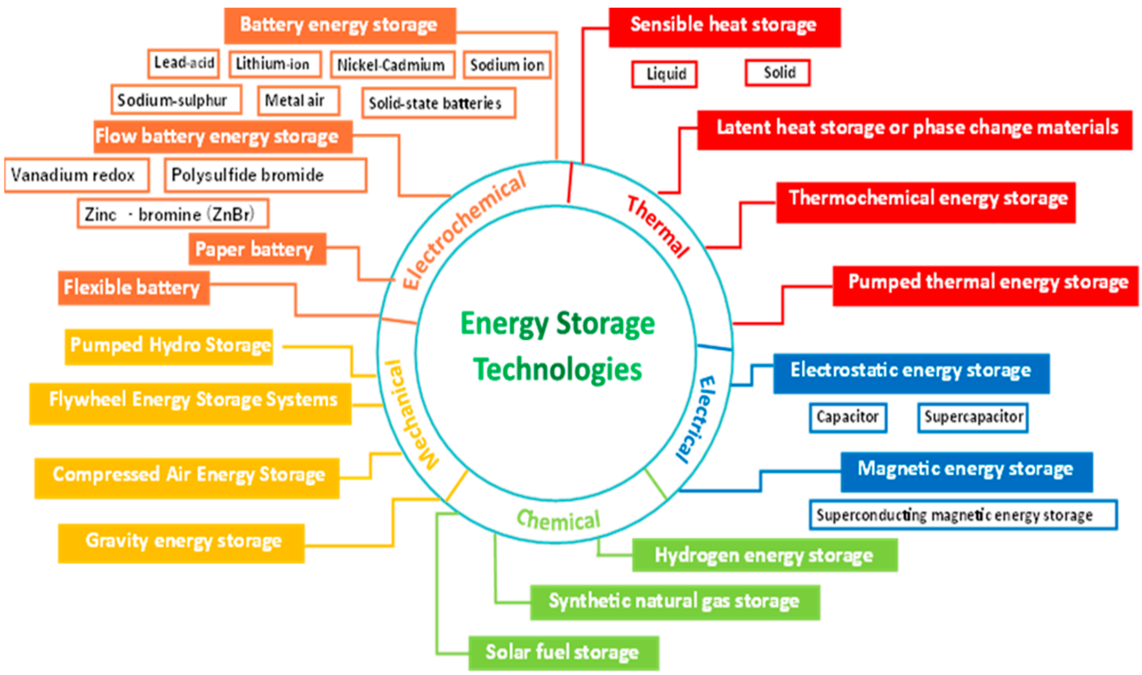

Figure 1. Energy storage technologies classification.

2.2.1. Mechanical Energy Storage System

Mechanical energy represents the energy that an object possesses while in motion (kinetic energy) or the energy that is stored in objects by their position (gravity energy).

The exploitation of this type of energy using the power of heat, water, or air with turbines, compressors, or other systems, leads to the development of mechanical energy storage systems. In this case, the main systems are represented by pumped hydropower storage (PHS), flywheel energy storage systems (FESSs), compressed air energy storage (CAES), and gravity energy storage (GES) [45].

- Pumped hydropower storage (PHS)

Pumped hydropower storage technology is based on two water reservoirs that are interconnected and located at different heights from each other. During surplus energy periods, the water is pumped from lower to higher reservoirs; therefore, mechanical energy is converted into potential energy. Extended demand leads to water release from the upper reservoir to the lower reservoir, making the hydraulic turbines operational and generating electricity [46].

The performance data for PHS facilities is detailed in Table 1 [46] presented below.

Table 1. Performance data for pumped hydropower storage systems.

Parameter	Values
Power range	10 MW–3.0 GW
Energy range	Up to 100 GWh
Discharge time	10–12 h
Life cycle	Technically unlimited
Reaction time	Some seconds–a few min
Life duration	>80 years
Efficiency	70–85%
Energy (power) density	0.5–3 Wh/kg

High efficiency, a long storage period, and a large storage capacity are the most important characteristics that contributed over the years to human well-being [47].

- Flywheel energy storage (FES)

Flywheel energy storage systems, which are considered mechanical batteries, have been used to store and transfer mechanical energy to and from the flywheel using an electric machine. The charging mode involves the use of electrical energy from the network in order to rotate the flywheel at very high speeds to generate kinetic energy, which will then be stored. In the case of the discharge mode, the rotor decelerates and the electric machine that acts similar to a generator converts the kinetic energy stored in the flywheel into electrical energy [48].

With a history of over 100 years, flywheel energy storage systems are currently used in high-tech applications. This is due to the discovery of new high-strength materials (glass fibers, carbon fibers, Kevlar), which allow very high-speed rotations (100,000 rpm) [49].

In the early development, these systems were used only in static applications, while in the last decades, they began to be used in mobile applications as well. The high specific energy that FESSs can store makes them attractive in the space field, as well as in the automotive field and in the construction of hybrid vehicles [48].

In Table 2, the most important parameters for flywheel energy storage systems are presented.

Table 2. Performance data for flywheel energy storage systems.

Parameter	Values	References
Power range	5–10 kW/kg	[48]
Energy range	200 Wh/kg	[48]
Life duration	Long	[50]
Efficiency	90–95%	[48]
Energy storage capacity	140 Wh	[50]
Life cycle	Unlimited	[48]
Discharge time	Minutes	[50]

Their high performances indicated that flywheel energy storage systems could be well-suited for many applications, including power quality improvement, renewable energy integration, and frequency regulation (to maintain the frequency of the electrical grid) [50].

- Compressed Air Energy Storage (CAES)

One of the many ways that energy can be stored for a long period of time is a compressed air energy storage system. Using CAES technology, the electricity surplus from the grid is used to compress the air with a rotary compressor and store it in an underground cavern. When the energy demand is high, the pressurized air is brought to the surface and passed through an air turbine that generates electricity [39].

Geostatic pressure is a crucial aspect of compressed air storage in optimal conditions. Therefore, high-quality rock deep in the ground, salt mines, and underground natural gas storage caves are the most appropriate options for compressed air storage [51]. Table 3 presents the most important aspects regarding performance data for compressed air energy storage systems [39].

Table 3. Performance data for compressed air energy storage system [39].

Parameter	Values
Capacity	0.1–1000 MW
Duration of storage	Long term (>1 year)
Type of storage	Potential energy
Lifetime	30 years
Response time	3–15 min
Duration of discharge at maximum power level	4–24 h
Round up efficiency	60–75%
Energy density	~3 Wh/mol
Cost	517 USD/kW
Operating temperature	Normal atmospheric

Despite their impressive data performance, improvements are still needed, so CAES technology is still under development. Researchers are developing new technologies to improve the efficiency, cost, and environmental impact of CAES facilities [52].

- Gravity energy storage (GES)

Gravity energy storage (GES) technology relies on pumped hydropower storage principles, which are based on storing electricity with potential energy. Therefore, the GES system operates by lifting heavy objects such as large masses of rocks, using excess energy available when the grid is disposed of extra energy. When energy is required, the objects are returned to their original position and potential energy is turned back into electricity with a generator [53].

In contrast to PHS, which has some limitations regarding geographic conditions, the energy storage system based on GES uses high-density solids as heavy objects in order to improve geographical adaptability, energy density, cycle efficiency, and economic performance [54].

Table 4 presents the technical characteristics of a gravity energy storage system [55].

Table 4. Performance data for gravity energy storage systems [55].

Parameter	Value
Energy density	1.06 J/m^3
Power density	3.13 W/m^3
Power rating	40–500 MW
Discharge time	34 s
Storage duration	Hours-one month
Lifetime	30+
Cost	1000 USD/kW
Efficiency	75–80%

2.2.2. Electrochemical Energy Storage (EcES) System

Electrochemical energy storage (EcES) systems are a traditional way to store energy for power generation. The chemical energy stored in this type of system is converted back into electrical energy when this is necessary. There are three categories of EcES systems that can be classified as batteries, electrochemical capacitors, and fuel cells.

- Battery energy storage (BES)

Battery energy storage represents the most common type of EcES system. They are made up of two electrodes, an electrolyte, and a separator. The electrodes store the chemical energy, and the electrolyte allows the ions to flow between the electrodes. When the battery is discharged, the chemical energy is converted into electrical energy [56].

There are two types of batteries: primary and secondary. Primary batteries, the so-called single-use batteries, are characterized by the non-reversibility of electrochemical reactions [57]. On the other hand, a secondary battery is a device that stores chemical energy and then converts it back into electricity in a reversible way.

Battery technology is currently under significant development processes. Batteries are being designed in various forms depending on the application type. Some of them are available on the market, while others are still in the experimental stage [58].

In the following sections, a brief description of the characteristics of secondary battery types is provided.

The lead-acid battery is considered the most popular and, at the same time, the earliest energy storage device (developed in 1859 by the French physician Gaston Planté). Rechargeable lead-acid batteries are based on a simple working principle of lead electrodes in aqueous electrolytes with sulfuric acid. On the other hand, the complex processes of charging and discharging have led to the continuous development of this energy storage device (Figure 2) [59].

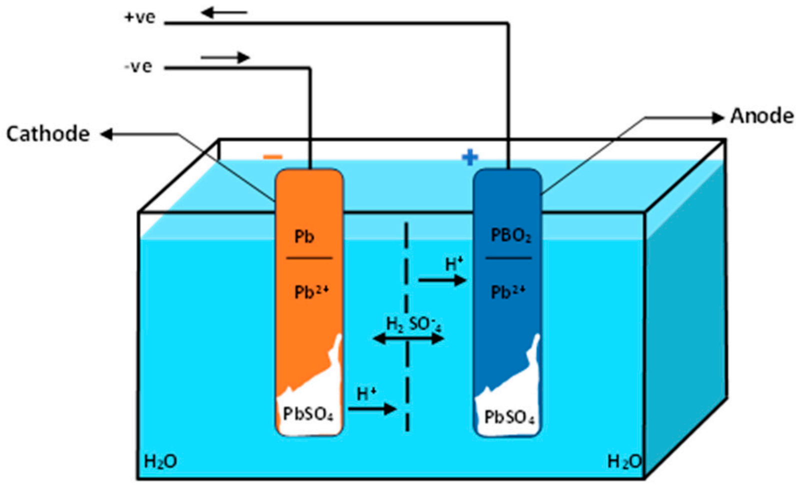

Figure 2. Schematic Diagram of A Lead-Acid Battery, adapted from [60].

This type of secondary battery remains a well-known solution in transportation applications like electric or hybrid vehicles. In the year 2022, the global lead-acid battery market was estimated at USD 27.82 billion and is expected to achieve a value of USD 47.80 billion by 2030 [61].

The combination of high energy and power density ensures the popularity and widespread use of lithium-ion batteries in applications in the electronic and transportation fields, especially in portable electronics, power tools, electric grids, hybrid, and fully electric vehicles [62]. Figure 3 presents the main components of a lithium-ion battery.

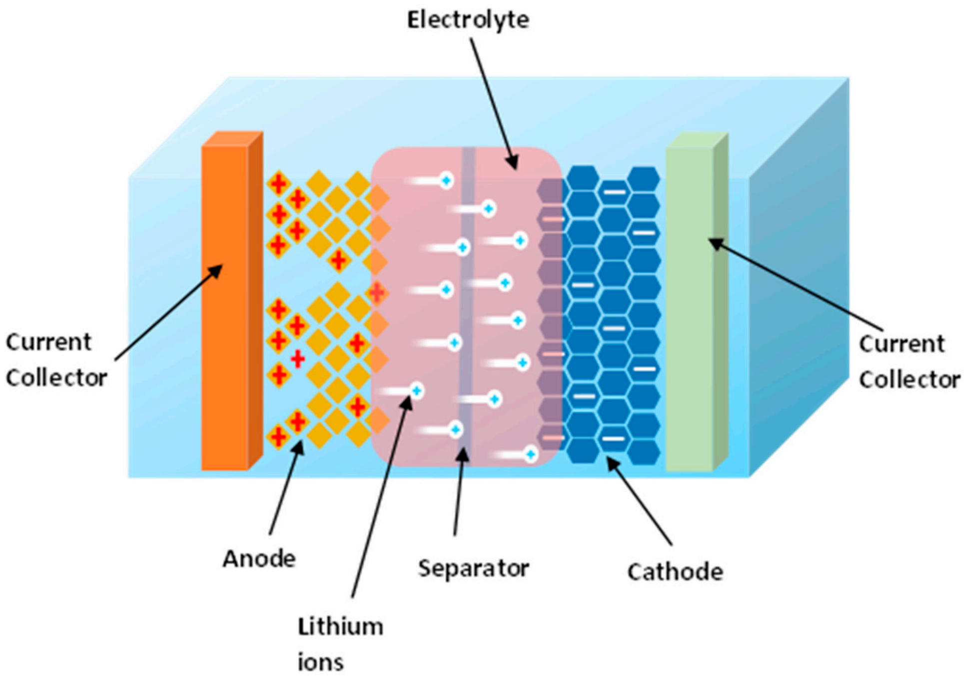

Figure 3. Lithium-ion battery components, adapted from [63].

Li-ion battery operability is based on the lithium-ion mobility between the negative electrode and the positive electrode during the discharging process and back when the charging process occurs [64].

The necessity and importance of reducing greenhouse gas emissions led to the large-scale recent development of new generations of batteries.

On the other hand, the extensive development of this type of energy storage technology may involve a future problem regarding the shortage of Li or other metals currently used in the manufacture of Li-ion batteries. Another challenge for the battery industry is the large amount of generated waste. This implies finding environmentally friendly solutions that have the main purpose of extending life cycles, improving recyclability, and reducing waste [63].

Nickel-cadmium (Ni-Cd) batteries have a history of over 100 years, and they compete for the same position regarding age and technical characteristics as lead-acid batteries (Figure 4). Ni-Cd batteries have a high power and energy density (50–75 Wh/kg) and a higher number of cycles (>3500 cycles) compared with lead-acid batteries [65].

The main disadvantage of Ni-Cd batteries is the relatively high cost of the manufacturing process. In addition, one of the component elements (cadmium) is known to be a toxic heavy metal; therefore, this implies a restriction on the use of Ni-Cd batteries, and over time, these types of batteries have disappeared from many fields of applications [66].

Before losing its popularity, this type of rechargeable battery was used in power tools, home electronics, and toys [67].

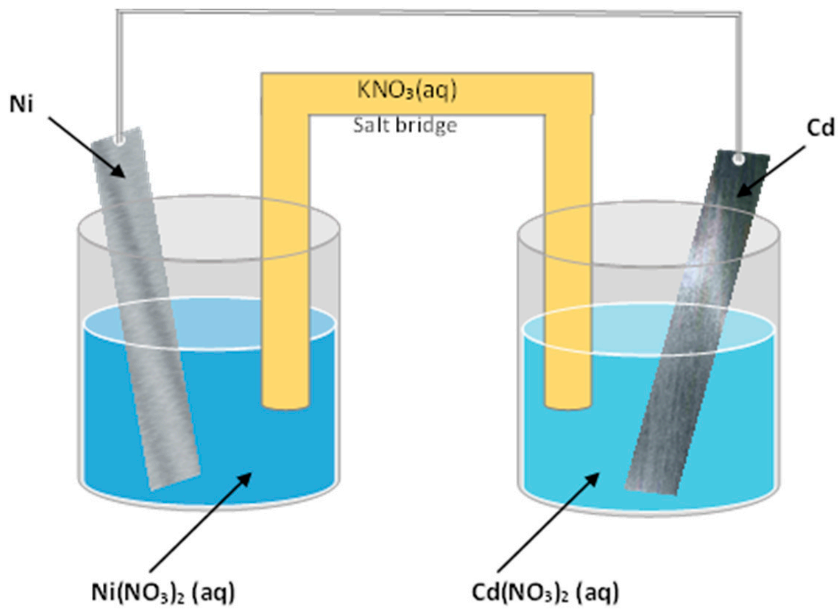

Figure 4. Operation scheme of a Ni-Cd battery [67].

Sodium-ion (Na-ion) batteries are also a type of electrochemical energy storage system that uses sodium ions (Na+) as charge carriers. This type of battery shows similarities with Li-ion batteries in terms of principal operation. Although sodium and lithium are found in the same group on the periodic table and have similar chemical properties, the energy storage systems that include each of the analyzed elements are different from each other [68].

There are four types of materials (carbonaceous, alloy, phosphoric, and sulfides or metal oxides) that can be used for the anode of a sodium ion battery, and same number of materials (layered O3, layered P2, polyanionic compounds, and Prussian blue analogs) that can be used for the cathode. The specific type of material that should be used depends on the desired performance characteristics of the battery, such as its energy density, power density, and lifetime [69].

Figure 5 presents a schematic of the Na-ion battery cell. It can be observed that the structure is similar to Li-ion batteries.

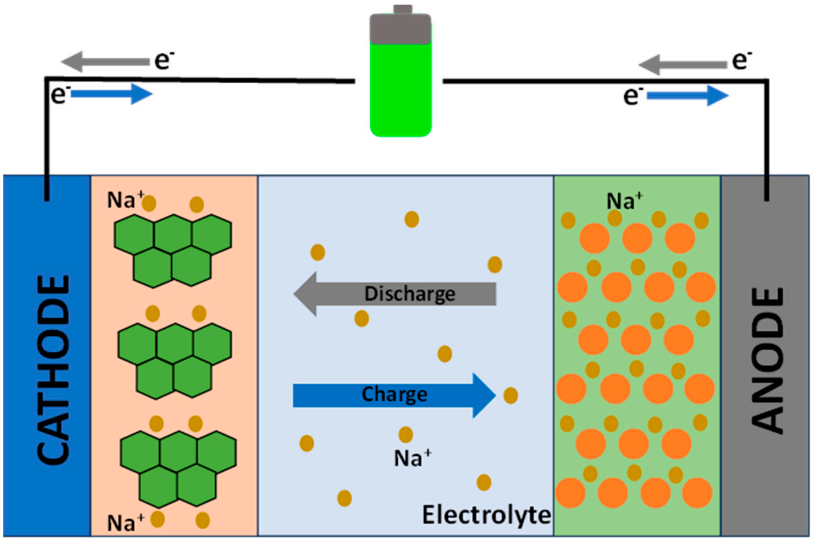

Figure 5. Schematic representation of a Na-ion battery cell [70].

Sodium-sulfur (NaS) batteries rely on molten salt technology, which includes molten sulfur as the positive electrode and molten sodium as the negative electrode, both separated by a solid beta alumina electrolyte (Figure 6). However, this type of energy storage system has the important characteristic of operating at high temperatures (over 300 °C) [71].

The sodium-sulfur battery is highly promising equipment due to its high efficiency, high power density, extended lifetime, and 80% discharge depth [72].

NaS batteries are used for large-scale non-mobile applications, such as grid energy storage. The major applications include backup power, load leveling, and renewable energy stabilization [73].

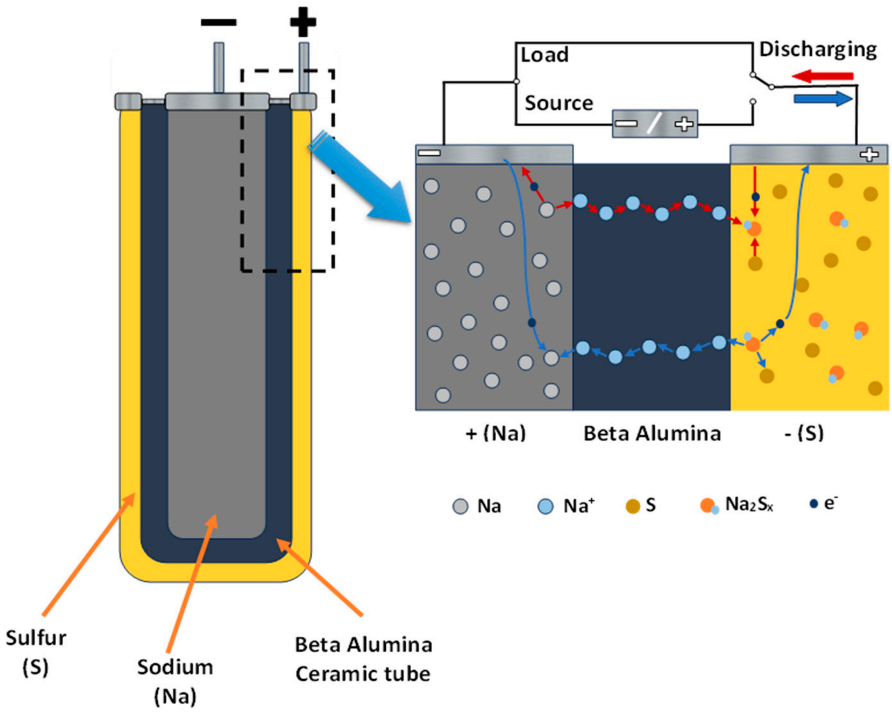

Figure 6. Sodium-sulfur NaS battery structure [73].

The special characteristics of metal-air batteries, including specific capacity and energy density, make them ideal for successful usage as energy storage devices. This type of battery consists of a metal anode, oxygen from atmospheric air, an air cathode, a separator, and an electrolyte (Figure 7). Inside metal-air batteries, an electrochemical reaction occurs between the metal anode and oxygen gas. Depending on the anode type, the electrolyte is selected. Therefore, the electrolyte can consist of an aqueous solution (potassium hydroxide), a non-aqueous solution, a neutral solution, a hybrid, and a solid state. The anode used in metal-air batteries can include Li, Na, Fe, Zn, Al, K, and other metals with excellent electrochemical equivalence [74,75].

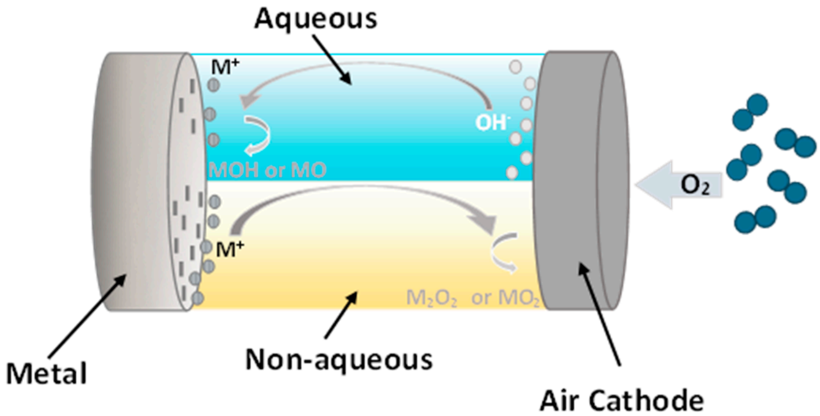

Figure 7. Metal-air battery structural form, adapted from [74].

Due to its great opportunities and excellent properties, this type of energy storage system has achieved impressive progress during the last few years [71].

A solid-state battery (SSB) is an energy storage system that uses a solid electrolyte instead of a liquid electrolyte that is specific to the lithium-ion battery, as can be seen in Figure 8. The main component of a solid-state battery is the solid electrolyte, which can be made from ceramic, glass, polymer, or a mixture of these materials [76].

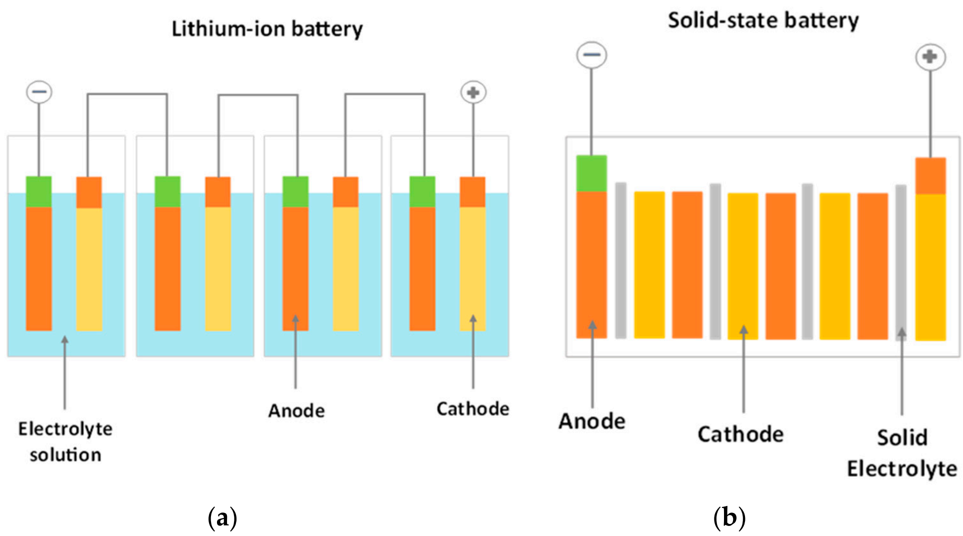

Figure 8. Lithium-ion battery (**a**) vs. solid-state battery (**b**) structures.

The cell chemistry of an SSB is similar to the cell chemistry of a liquid electrolyte battery, but the solid electrolyte offers several advantages, including higher energy density, higher safety, and a wider operating temperature range. However, SSBs are also more expensive and more difficult to manufacture than liquid electrolyte batteries [77].

SSBs are still in the early stages of development, and there are several challenges that need to be overcome before they can be commercialized on a large scale. One challenge is that SSBs can be more difficult to manufacture than traditional lithium-ion batteries. Another challenge is that the solid electrolytes used in SSBs can have lower ionic conductivity than liquid electrolytes, which can limit the charging and discharging rates of SSBs [78].

- Flow battery energy storage (FBES)

The working principle of flow a battery energy storage (FBES) system consists of energy storage in two liquid electrolytes that are pumped through electrochemical cells. When the battery is charged, an electric current is applied to the cells, which causes the oxidation and reduction of ions from the electrolytes. When the battery is discharged, the ions in the electrolytes flow back through the cells, generating an electric current [79].

The energy density of such systems is entirely dependent on the volume of the electrolyte being stored. Power density in flow battery systems is essentially dependent on the rates of the electrode reactions occurring at the anode and the cathode [80].

This type of storage energy system offers several advantages over other types of batteries, such as a longer lifespan, higher safety, and scalability. As the challenges (lower energy density and higher costs) that arise in FEBS systems are solved, they are expected to be used in a wide range of applications [81].

- Paper batteries

Paper batteries represent a type of battery that uses paper as the substrate and electrodes. They are typically made by printing electrodes onto paper and then adding an electrolyte. The development of this type of battery is still in progress, but they have the potential to be low-cost, flexible, and disposable. Paper is a cheap and abundant material, and the electrodes can be printed using inexpensive printing methods. Additionally, paper batteries are lightweight and flexible, which makes them suitable for a variety of applications. The disposable property makes paper batteries a good choice for applications where single-use batteries are needed, such as in medical devices or environmental sensors [82].

The disadvantage of paper batteries is that they have a lower energy density than other types of batteries, such as lithium-ion batteries. This means that they cannot store as much energy in the same volume. Additionally, paper batteries have a shorter life cycle than other types of batteries, meaning that they need to be replaced more often [83].

- Flexible batteries

Wearable electronics are developing rapidly, so designing and building flexible power supplies, especially rechargeable lithium-ion batteries, is necessary. These batteries should be high-performance, flexible, and durable enough to be integrated into electronics. To make electrode materials with high repeated resistance on bending, twisting, and stretching, researchers are developing and manufacturing materials with highly flexible high energy and power density properties that can cycle many times without losing performance. Another condition that materials must fulfill is the compatibility with the electrolyte and separator used in the battery [71]. This means exploring a range of soft carbon, metal and polymer materials, as well as new manufacturing methods to create complete batteries [84].

2.2.3. Thermal Energy Storage (TES)

Thermal energy storage (TES) systems represent a process of storing energy by changing the temperature, phase, or chemical bonds of a material. The materials are stored at high or low temperatures in a thermal-insulated tank, depending on the desired operating temperature range. The stored energy can then be recovered and used for a variety of residential and industrial applications, such as space heating or cooling, hot water production, or electricity generation [71].

There are many different types of TES systems, but they all work on the same basic principle: heat is transferred into a storage medium where it is stored until it is needed. The storage medium can be a solid, liquid, or gas, and it can be stored in a variety of ways, such as in a tank, underground reservoir, or phase change material [85].

- Sensible heat storage (SHS) systems

Sensible heat storage (SHS) is a thermal energy storage technology that stores heat by raising the temperature of a material (either solid or liquid). The amount of energy that can be stored depends on the specific heat of the material (Equation (1)).

$$E_{sensible} = \rho V \int_{T_C}^{T_H} c_p(T) dT; \tag{1}$$

The specific characteristics of sensible storage materials include large densities, ρ (kg/m^3), large specific heats, c_p (J/kg–K), and large temperature differences between the hot and cold states, T_H–T_C (K) [86].

Water is the most common liquid used for SHS, but other materials such as molten salts and rocks are also used. A storage tank and a heat exchanger are the principal components of which an SHS system is made. The storage tank is filled with the storage material, and the heat exchanger is designed to transfer heat between the storage material and the working fluid. The working fluid serves as a fluid that is used to heat or cool the required application. This type of energy storage system is designed to store heat from a variety of sources, such as solar energy, industrial waste heat, and geothermal energy. The stored energy can then be used to heat and cool buildings, generate electricity, and power industrial processes. SHS systems are relatively simple and inexpensive to obtain, and in addition, these systems have an important characteristic in this field: high energy storage density. However, one major inconvenience of SHS systems is that they can only store heat at a single temperature [87].

- Latent heat storage (LHS) systems

Latent heat storage (LHS) is a thermal energy storage technology that uses the latent heat of phase change materials (PCMs) to store and release thermal energy. PCMs are materials that can absorb or release a large amount of heat as they change phase from solid to liquid, or vice versa [86].

LHS systems work by transferring heat to or from the PCM, causing it to melt or solidify. During the melting process, the PCM absorbs heat from the surroundings, and during the solidification process, the PCM releases heat to the surroundings. The amount of heat that can be stored or released by an LHS system depends on the latent heat of fusion of the PCM and the mass of the PCM. Table 5 shows the thermophysical properties of a wide variety of materials that can be used for latent heat storage. The most common materials used in this type of energy storage are water, paraffin wax, salts, and metals. Water is the simplest and most inexpensive latent heat storage material, but it has a relatively low melting temperature. Paraffin waxes have higher melting temperatures and latent heat of fusion, but they are more expensive than water. Salts and metals have even higher melting temperatures and latent heat of fusion, but they are the most expensive latent heat storage materials. However, some liquid/gas substances, such as nitrogen and oxygen, can also be used for latent heat storage, especially for grid energy storage applications [88].

- Thermochemical energy storage (TCES) systems

Thermochemical energy storage (TCES) is a type of energy storage that uses reversible chemical reactions to store and release heat. This contrasts with other energy storage technologies, such as batteries and pumped hydro storage, which store energy in the form of electrical or mechanical energy, respectively [89].

TCES works by storing energy in the form of chemical bonds. During the charging process, heat is used to drive a chemical reaction that produces two or more products. These products can then be stored for long periods of time without losing any energy. When energy is needed, the products are reacted back together to release heat [89].

Among the advantages of TCES over other energy storage technologies are a very high energy density (storing a lot of energy in a small volume) and efficiency (round-trip efficiencies of up to 80%). Additionally, TCES systems can be used to store energy for long periods of time, even years [90].

There is a wide range of potential uses for thermochemical energy storage systems that include the storage of solar heat provided by the sun for use in space heating, water heating, and power generation. Another application of TCES systems is represented by waste recovery heat from industrial processes to be used in electricity generation. TCES has an essential role in maintaining a clean environment, by storing the excess electricity that comes from renewable energy sources [89,90].

However, TCES systems are still in development, and there are some challenges that need to be addressed before they can be widely deployed. One challenge is that some TCES reactions can be slow. Another challenge is that some TCES materials can be corrosive. Despite these challenges, TCES is a promising technology for energy storage. It has the potential to help us store and use renewable energy more efficiently and to reduce our reliance on fossil fuels [91].

Table 5. Thermophysical properties of different storage materials at standard conditions [86].

Storage Material	Melting Temperature (°C)	Specific Heat Capacity (kJ/kg·K)	Latent or Reaction Heat (kJ/kg)	Density (kg/m^3)
Aluminum	660	1.2	397	2380
Aluminum alloys (ex. Al-0.13Si)	579	1.5	515	2250
Water	0.0	4.18	334	997
Paraffin wax	40–60	2.1–2.5	180–250	800–900
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	222	1.5	100	1950
Lithium hydride	683	8.04	2582	790
Silicon	1414	0.71	1800	2300

- Pumped thermal energy storage (PTES) systems

Pumped thermal energy storage (PTES) is a technology that offers a perspective on large-scale energy storage. This energy storage system is based on a heat pump that uses grid electricity to alternate heat from low-temperature storage tanks to high-temperature storage tanks, creating stored energy that can then be used to generate power as needed. The materials that make up the tank are very important because they must have the ability to store heat at very high temperatures. One of the typical tank materials is molten salt [92].

PTES systems typically work using a Joule-Brayton cycle, which is the same cycle used in gas turbine power plants. The cycle consists mainly of four steps: compression, heating, expansion, and cooling [93].

PTES systems have several advantages over other energy storage technologies. They are highly efficient with round-trip efficiencies of up to 80%. They can also store large amounts of energy, making them ideal for long-duration energy storage applications. Additionally, PTES systems are relatively low-cost and have a long lifespan [94].

2.2.4. Electrical Energy Storage (EES) Systems

Electrical energy storage systems conserve energy in an electric field instead of changing it into another form of energy. There are two types of EES technologies available, each with its own benefits and inconveniences: electrostatic energy storage systems and magnetic energy storage systems.

- Electrostatic Energy Storage Systems

The most common type of electrostatic EES is the capacitor. Capacitors store energy by separating oppositely charged plates with a dielectric material. When the capacitor is charged, a voltage is created between the plates, which stores energy [95]. Among the benefits of an electrostatic energy storage system are high energy density due to the large amount of energy stored in a relatively small volume, high efficiency because this type of technology can store and discharge energy with very little loss, very quick response times to charge and discharge, and a long lifespan. On the other hand, electrostatic energy storage systems also have some inconveniences like high cost and limited power density [96].

Capacitors and supercapacitors are both electrostatic energy storage systems. The first category is the most common type of electrostatic EES. They are used in a wide variety of applications, including electronics, power electronics, and energy storage. On the other hand, supercapacitors, the second electrostatic energy storage system, are a type of capacitor with a very high energy density. Although research on supercapacitors is still in progress, supercapacitors have the potential to play a major role in future energy storage systems [95].

- Magnetic Energy Storage Systems

Magnetic energy storage systems (MES) are devices that store electricity in the form of a magnetic field with minimal loss of energy. The most popular type of MES is the superconducting magnetic energy storage (SMES) system. The energy stored using SMES systems is created by the magnetic field obtained in a superconducting coil. The superconducting coil current increases during the charging phase and decreases during the discharging phase. Superconducting materials possess the characteristic of having zero electrical resistance, which allows SMES systems to store large amounts of energy with minimal loss [97].

MES systems are a promising technology for energy storage. They offer several advantages, such as high energy density, high efficiency, and fast response times. However, they are still relatively expensive and require cryogenic cooling. As the technology continues to develop and become more affordable, MES is expected to play an even greater role in the future of energy [98].

2.2.5. Chemical energy Storage (CES)

- Hydrogen energy storage

Hydrogen can be used in energy storage technology in three forms, gaseous, liquid, and solid. Hydrogen gas can be compressed and stored in high-pressure tanks. This is the most common method of storing hydrogen, but it requires a lot of energy to compress the gas, and the tanks are heavy and bulky. Also, this element can be liquefied by cooling it to very low temperatures. Liquid hydrogen is much more energy-dense than compressed gas, but it is also more expensive and difficult to store. On the other hand, solid-state storage involves hydrogen can be stored in solid materials, such as metal hydrides and carbon nanotubes. Solid-state storage is still under development, but it has the potential to be the most efficient and cost-effective way to store hydrogen [71,99].

Hydrogen is considered a promising solution for integrating large amounts of renewable energy into the grid, as it can be used to store excess energy generated during periods of high renewable output, such as when the sun is shining or when the wind is blowing. Hydrogen energy storage has a series of advantages over other energy storage technologies. Hydrogen is very energy-dense, meaning that it can store a lot of energy in a small volume. It is also non-toxic, but one of the most important challenges of this technology is represented by the difficulty of storing hydrogen safely and efficiently [100].

Despite these challenges, hydrogen energy storage is a promising technology for the future. It has the potential to help us integrate renewable energy sources into the grid and to provide long-duration energy storage. Overall, hydrogen energy storage is a versatile and promising technology with a wide range of potential applications. As the technology continues to develop and costs come down, it is expected to play an increasingly important role in the global energy transition [17,100,101].

- Synthetic natural gas (SNG) storage

Synthetic natural gas (SNG) is a gas produced from a variety of sources, including renewable energy sources such as solar and wind power, biomass, and fossil fuels. SNG can be stored in the same way as natural gas, in underground caverns and high-pressure tanks. An important advantage of SNG technology is the potential to store a lot of energy in a small volume. Another benefit of SNG storage is that it can be used to store excess renewable energy obtained throughout the daytime and then discharge the energy when required (for example, when decreasing renewable energy production occurs). This can help to balance the grid and reduce reliance on fossil fuels [71,102].

SNG storage can also be used to provide long-duration energy storage. This is because SNG can be stored for long periods of time without losing its energy content. This makes it ideal for applications such as seasonal energy storage and backup power generation. SNG storage is a versatile and promising technology with a wide range of potential applications, including grid-scale energy storage, transportation, industrial applications, and residential and commercial applications [103].

- Solar fuel storage

Solar fuel is considered a synthetic fuel that is produced using solar energy. A wide range of sources are used to produce this type of fuel, such as water, carbon dioxide, and biomass. Solar fuel storage is a method for storing solar energy in the form of chemical fuels. This can be performed using a variety of processes, such as photocatalysis, thermochemical cycles, and artificial photosynthesis. Solar fuels are very energy-dense, non-toxic, and non-flammable. There are various categories of solar fuels, but some of the most promising are hydrogen, methanol, and formic acid. Hydrogen can be produced from water using solar energy and can be used in numerous applications, including transportation, power generation, and industrial processes. Methanol can be produced from carbon dioxide and hydrogen using solar energy, and it contributes to applications such as gasoline blends, fuel cells, and direct methanol fuel cells. Formic acid is obtained from carbon dioxide and hydrogen using solar energy and can be used in fuel cells, direct formic acid fuel cells, and as a hydrogen storage material. For instance, hydrogen can be stored in compressed gas tanks, liquid hydrogen tanks, or metal hydrides. Methanol can be stored in liquid tanks or the form of methanol-based hydrates. Formic acid can be stored in liquid tanks or in the form of formic acid-based hydrates. The challenges associated with this type of energy storage technology include the inefficiency of solar fuel production processes and the safety and efficiency of storage. Nevertheless, this versatile and promising technology has great potential to integrate renewable energy sources into the grid and to provide long-duration energy storage [8,71].

3. Lithium-Ion Batteries

Concerns related to global environmental situations, such as climate changes, are driving energy and mobility transformations to respond to the most important environmental problems regarding energy storage technologies. To facilitate the energy transition toward a neutral climate, lithium-ion batteries are a key technique [104,105]. In the past decades, lithium-ion batteries with different chemical compositions have been used for different applications, such as portable electronic devices and stationary systems, and in the transportation industry [106]. The intensive use of electric vehicles led to a growth in lithium-ion batteries demand because of the critical role they have in the entire system of a vehicle. To improve mobility, obtaining lighter batteries with superior energy density is an important goal; therefore, sustained developments in battery technologies increase safety during exploitation and the life cycle [107]. Usually, the ecological impact of the transport industry is related to the usage phase, so it is dependent on the fuel source. Electricity stored in batteries is the main primary fuel source for electric vehicles; therefore, efficient storage and usage technologies are the key to the sustainable development of the mobility sector [108].

As the main component of electric vehicles, batteries play a considerable role in the environmental capabilities of the system. Lithium-ion batteries, compared with nickel-metal hydride, nickel-cadmium, and lead-acid batteries, have superior power density, higher energy, and a smaller environmental footprint [109]. To comply with the ecological requirements, another important aspect is related to valorizing the residual capacity of used lithium-ion batteries using different energy storage technologies, such as photovoltaic panels or different portable devices [110]. Additionally, after the energetic potential is exhausted, repairing or recycling valuable components (e.g., cobalt, lithium, etc.) will bring important ecological advantages. Therefore, assessing the life cycle of lithium-ion batteries could offer a wider perspective of the ecological impact and the possibilities of extending the working time and improving recyclability to decrease consumption [111].

The assessment and quantification of the environmental impact of lithium-ion batteries are useful in identifying the main challenges and effective ways to implement the concept of sustainable development in the case of new-generation batteries [112]. In this context, a detailed evaluation of the ecological impact of the main stages, including production, use, repair or reuse, and recycling processes is required.

3.1. Production and Use Phases of Lithium-Ion Batteries for Electric Vehicles

Before the large-scale production of lithium-ion batteries, the most used batteries used in electric vehicles were based on nickel-cadmium (Ni-Cd), lead-acid (Pb-Ac), and nickel-metal hydride (NiMH) [113,114]. By analyzing the life cycle, it was observed that NiMH batteries have the lowest environmental impact, although the recycling process is difficult to complete because of inappropriate infrastructure. On the other hand, Pb-Ac and Ni-Cd have high recyclability potential, but the main problem is their increased toxicity. Considering a comparative analysis of life cycles, it can be concluded that Pb-Ac, Ni-Cd, and NiMH batteries have a similar environmental impact, but their impact is much higher compared to Li-ion batteries [115].

Starting with the commercial production of Li-ion batteries, lithium-iron phosphate (LFP) batteries, nickel-manganese-cobalt (NMC) batteries, and lithium-manganese oxide (LMO) batteries are now widely used in the electric vehicle production processes. For NMC batteries, the environmental impact gradually decreased with the evolution of NMC 111, NMC 523, NMC 622, and NMC 811. An analysis of the impact of NMC batteries on energy demand [113] observed that the production stage of the material brings higher ecological damage. The main factors that support this conclusion are related to obtaining cathode and electrolyte materials using significant quantities of water and generating greenhouse gas emissions (SO_x, NO_x, or PM10). Kelly et al. [116] highlighted that the production of different materials and components suitable for batteries has a major impact on the battery life cycle and the generated pollutant emissions, as well as water and energy consumption.

A comparative study on the life cycle analysis of LFP and LMO batteries indicated that the first category has a higher ecological impact. However, LFP batteries have superior operational performance; therefore, a reduced number of LFP batteries is needed over an electric vehicle life cycle [117,118]. A parallel study on the life cycle assessment of LFP and NMC indicated that these two categories of batteries have different environmental impacts at different stages. LFP batteries have a lower environmental impact in the production stage, while NMC is more environmentally friendly in the use and transport stages. Throughout their life cycle, LFP batteries have a reduced environmental impact. Also, due to their heavier mass, they offer numerous benefits when reused in energy storage [119]. Comparing the greenhouse gas emissions generated in the production processes for the three types of batteries, it was found that LFP generates 3061 kg CO_2, LMO generates 2912 kg CO_2, and NMC generates 2705 kg CO_2. These values are 30% higher compared with the production processes of the vehicles equipped with internal combustion engines [120].

The batteries currently used in the electric vehicle production stage have different advantages and disadvantages, so it is difficult to identify which type of battery has a lower pollution degree. However, an important factor is that Li-ion batteries are superior to Ni-Cd, Pb-Ac, and NiMH, which means that the technology used nowadays is less polluting. In the battery production stage, energy consumption and pollutant emissions are higher for the processing of the cathode and the electrode materials. While using batteries, performances have been improved by up to 60% [121,122]. Therefore, the use of "green energy" and the improvement in battery production technologies contribute significantly to reducing the impact on the environment and promoting electric vehicle exploitation.

3.2. Reuse of Retired Lithium-Ion Batteries

After losing approximately 20–30% of their initial capacity, lithium-ion batteries can no longer be used according to their initial purpose [123]. Furthermore, because of their large storage capacity, the reuse of Li-ion batteries represents an attractive alternative. In this context, there are two ways to reuse Li-ion batteries: remanufacturing and repurposing [124].

1. The remanufacturing of retired lithium-ion batteries refers to their repair and reconditioning to be able to be used in the same applications (e.g., electric vehicle industry). Xiong et al. [125] determined the environmental impact and remanufacturing cost of NMC batteries to verify the feasibility of this process. The obtained results were compared to data from the new battery production process. The investigation showed that both energy consumption and greenhouse gas emissions were lower for battery remanufacturing processes, and the costs were reduced by approximately 40% [123].
2. The repurposing of retired lithium-ion batteries involves reconfiguring batteries for different applications where low voltage is needed, such as power tools or auxiliary services. Using retired lithium-ion batteries from electric vehicles in stationary energy storage technologies can increase the energetic efficiency and reduce costs while bringing substantial ecological and economic advantages [126]. More exactly, using retired batteries in different applications extends the life cycle of the product and reduces the environmental footprint, including a substantial decrease in greenhouse gas emissions [127].

3.3. Recycling Lithium-Ion Batteries

After the secondary use, lithium-ion batteries can be recycled, to recover their primary components. This process has a major role because recycled lithium-ion batteries can be reintroduced into the economic circuit and reduce the global demand for raw materials. To highlight the recycling benefits, Hao et al. [128] compared the energy consumption and greenhouse gases generated during the production stage of electric vehicles, which would be partially and totally recycled. It has been observed that carbon emissions can be reduced by applying these processes. At present, recycling processes mainly focus on metal recovery from the cathodic material using pyrometallurgical, hydrometallurgical, direct-regeneration, or bio-leaching processes [129].

Pyrometallurgy involves the removal of non-metallic materials using pyrolysis at high temperatures in a metallurgical furnace, followed by the melting of precious metals using molten salts. Thereafter, the metals of interest are recovered by applying magnetic and gravity separation, flotation, and hydrometallurgical treatments [130]. Pyrometallurgy has simple operation stages and can be easily applied to a wide range of wastes from lithium-ion batteries, but requires a high initial investment, is energy-consuming, and is potentially a toxic gas generator. Additionally, this method cannot efficiently recover lithium or recycle the anode or electrolyte [131].

Hydrometallurgy involves pre-treatment, leaching, and metal recovery stages. This complex process includes leaching in inorganic and organic acids, the use of alkaline substances, and eutectic leaching solvents. It was observed that high quantities of acidic wastewater are produced, even if the efficiency of leaching processes in inorganic acids is high [132]. Other leaching methods do not produce acidic wastewater, but the process speed is low and needs reducing acids or a combination of mechanochemical methods or ultrasonic treatments to improve the leaching effects. Generally, the main challenges that hydrometallurgy faces are the complexity of processing stages and the generated wastewater. Given the advantages such as the rapidity of the process, low degree of impurities, and reduced costs, hydrometallurgy has a greater potential to reduce environmental impacts compared with pyrometallurgy [133].

The main purpose of direct regeneration is the repair of the crystalline structure and the electrode without applying leaching procedures. Combining direct regeneration with different methods, like pretreatment or physical separation, can affect the cathode material, and this can become inappropriate for use in lithium-ion batteries. In this case, re-lithiation and annealing treatment must be applied to reach the initial composition or to repair the structural defects, and, therefore, the cathode could be used in the assembly of a new battery. Direct regeneration can be considered a non-destructive repair technology. The methods used for direct regeneration can be divided into three classes: direct heat treatment, solid-state sintering, and the hydrothermal method [134,135]. These processes have important advantages, like simplicity of the process, low costs, and reduced quantity of the generated pollutant emissions. However, the direct regeneration method has some limitations, such as the impossibility of complete repair of the material structure [135].

Bioleaching uses bacteria and microbes to extract metals from ores and waste materials. During these processes, microorganisms produce leaching agents such as sulfuric acid or other organic acids, which dissolve metals from ores or other secondary resources [5]. Recycling Li-ion-based batteries using bio-leaching can extract the metallic constituents and reuse them in new Li-ion batteries to avoid waste and reduce the possibility of exposure to toxic constituents in the environment.

4. Environmental Impact of Reducing Potential by Replacing Fossil Fuels with Lithium-Ion Batteries

The intensive usage of fossil fuels has brought significant consequences in terms of environmental protection, including global warming, water, soil, and air pollution, and the depletion of primary resources. Even with the technological benefits that fossil fuels bring to society, the development of new solutions for reducing or totally replacing them in different industries became a necessity. An important element that should be considered in selecting the most appropriate technology storage materials for the transition to zero pollutant emissions is maintaining a comparable degree of the obtained performances to not people's everyday activities.

In the transportation industry, a potential candidate that can replace fossil fuels is lithium-ion batteries, whose usage performances are superior to and safety risks are smaller than those of other storage technologies. Since this technology started to be interesting in the transportation field a few years ago, its implementation implies some bottlenecks, especially related to the production stage (because of the generated pollutant emissions) and the recycling phase, to prevent long-term waste accumulation. In the next decade, battery demand is envisaged to exceed 3.2 TWh; hence, the development and implementation of environmentally friendly improvements are necessary. To decrease the environmental impact, a solution can be an improvement in the awareness level for all the involved parts, considering the supply chain. Another procedure that can be helpful is the increase in lithium-ion battery performance to extend the working life and avoid exhausting raw materials.

Designing lighter lithium-ion batteries is a measure that can ensure an increase in electric vehicle autonomy, an aspect that will make them more attractive to the public. In addition, an improvement in the working voltage, energy capacity, and thermal stability will encourage the total replacement of fossil fuel usage in the automotive sector.

Other important aspects that should be considered are maintaining low costs, especially for cathode materials, whose values exceed 30% of the total costs of a battery system. Therefore, developing new chemistries for cathode materials that can maintain performances on a high level represents a necessity that meets the present society's demands. To consider reducing the environmental footprint permanently during the entire lithium-ion battery life cycle, it is preferable to decrease the critical material content and design them to facilitate the recycling process.

In the present conditions, even if fossil fuel usage brings numerous technological benefits, lithium-ion batteries can be considered a promising solution for the future of the electric vehicle industry. Beyond their technical capabilities, the use of lithium-ion batteries considerably reduces environmental impacts, contributes to decoupling the industry from virgin resources, and encourages the industrial sustainable development of the transport industry.

5. Conclusions

Fossil fuels are a vital component of the transportation industry, owing to the technological capabilities generated by their usage. But excessive consumption causes serious damage to the environment by exhausting non-renewable resources. This aspect has a considerable negative impact on industrial sustainable development, particularly in the actual society, which is concerned with reducing the anthropogenic impact and, therefore, the consequences that the irrational use of primary resources can have on future generations.

Research performed in the last few years is intensively focused on identifying new materials or techniques with the potential to replace fossil fuels. Considering the main energy storage technologies, it can be observed they all have a common objective of decreasing the industrial environmental footprint and pollutant emissions, extending the life cycle, and improving recyclability from the design stage.

From the necessity of complying with these mission statements, most of the studies concluded that the most appropriate candidates for replacing fossil fuels are lithium-ion batteries, owing to the technological performances and safety in operation. These devices have the advantage of facilitating the transition to a transport based on electric vehicles and, therefore, to economic circularity and zero pollutant emissions in the future years. To achieve these goals, certain measures should be considered, such as optimizing the composition of used materials and obtaining processes to be more environmentally friendly. Another important component is increasing technological performances to be attractive and respond to the actual needs and demands of societies.

In conclusion, the continuous development and testing of new materials and technologies suitable for fossil fuel replacement makes a significant contribution to reducing the negative effects generated by pollution, improving actual living conditions, and promoting the preservation of natural resources for the next generations.

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