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Analysis of the present and prediction of the future of Li batteries applied to electric transport vehicles
Anàlisi del present i predicció de futur de les bateries de Li aplicades als vehicles de transport elèctrics

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Hem de tenir perseverança i sobretot confiança en nosaltres mateixos. Hem de creure que estem dotats per a alguna cosa, i que aquesta cosa, sigui el que sigui, ha de ser assolida.

Marie Curie

Aquest camí no ha sigut fàcil, i sense el suport de persones molt estimades no hauria arribat fins a aquest punt. En primer lloc, m'agradaria agrair al meu tutor Pere per guiar-me i ajudar-me en tot moment. També vull agrair als meus pares pel seu sacrifici i els seus ànims per continuar durant els moments difícils. Gracies de tot cor als meus germans i germanes per ser un suport essencial en aquest procés. Per altra banda, m'agradaria agrair als meus amics i amigues per l'estima i les xerrades necessàries quan es requerien. Finalment, vull agrair a la meva parella per acompanyar-me en tot moment i per ser sempre el meu refugi.

REPORT

IDENTIFICATION AND REFLECTION ON THE SUSTAINABLE DEVELOPMENT GOALS (SDG)

The SDGs are global goals established by the UN that are part of the 2030 agenda to address climate change, poverty and social inequalities. These SDGs are grouped into 5 areas (people, prosperity, planet, peace and partnership). Lithium batteries in electric vehicles are closely related to the identification and reflection on the sustainable development goals implemented by the UN. An important goal is to manufacture more vehicles with lithium batteries in the present and in the future in order to improve aspects such as the transition from more polluting energies to cleaner energies, sustainable mobility and the reduction of emissions on the planet. The SDGs most related to the topic of this bibliographic work are SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production) and 13 (climate action).

In the case of SDG 7, lithium batteries in electric vehicles make renewable energies a good way forward, since they can be charged electrically using wind or solar energy. The use of these batteries also minimizes dependence on fossil fuels. Another important point is innovation in technology and infrastructure, which are directly related to SDG 9. One of the most outstanding innovations thanks to their safety and autonomy are solid-state batteries. On the other hand, it is also necessary to develop an adequate infrastructure for the evolution of electric vehicles. It is vitally important to have a distribution of abundant charging points to facilitate the correct operation of transport and electric vehicles. One of the solutions in the case of infrastructure is the deployment of smart electrical networks (Smart Grids). These optimize the distribution of electricity in electric vehicles to be able to charge them without causing overloads within the electrical system.

Electric cars have a great urban impact, which is related to SDG 11. Electric transport has great advantages for making cities sustainable, such as reducing noise and air pollution. The promotion of electric public transport such as buses means that the use of fossil fuels is replaced to improve air quality in cities and, therefore, evolve to a more ecological system.

It should be noted that the production and recycling of lithium batteries is a challenge in several countries due to its environmental impact. Large amounts of water are needed, and problems arise of damaging the ecosystem due to the degradation of mineral areas during the extraction of basic components that can be contained in batteries, such as lithium, nickel and cobalt. This issue is directly related to SDG 12. The objective would be to produce batteries that are suitable for participating in a recycling process implementing a circular economy to give them a second useful life and reuse them.

Finally, it is vitally important to think about the climate change that our planet is suffering. Replacing fuels with lithium batteries means that there are fewer carbon dioxide emissions, and that energy efficiency is higher than in vehicles that use fuel as an energy source for their mobility. By reducing greenhouse gas emissions, we would decarbonize transport vehicles and evolve towards a more sustainable future in which we would not suffer from the phenomenon of global warming. Improving climate change by implementing lithium batteries in electric vehicles has a great relationship with SDG 13.

To achieve these goals set by the UN in relation to lithium batteries in electric vehicle applications, it is necessary to move towards improving production, innovation and recycling processes. To address these changes, it is necessary to overcome current challenges such as accessibility to technology around the world, expanding the charging infrastructure for electric vehicles, and reducing manufacturing and market sales costs.

CONTENTS

1. SUMMARY

Conventional combustion cars are a problem due to their high CO_2 emissions. It has been calculated that a quarter of carbon dioxide emitted by human activities comes from transport vehicles. The objective is to decarbonize vehicles by electrifying them with the use of lithium batteries as an energy source that allows their mobility to evolve towards a more sustainable future. The bibliographic analysis shows the different types of lithium batteries that can be useful in vehicles and the forecast of the evolution according to the different scenarios, costs, available materials and performance. Lithium-ion batteries are the most used currently and vary according to the composition of the cathode. The most prominent currently are NMC (nickel-manganese-cobalt) and LFP (lithium iron phosphate) There are also other types of lithium batteries that are used less often, such as Li-polymer, which are one of the options used in some light electric vehicles. Emerging technologies and innovations are key to developing Li-ion batteries with materials that can improve consumption thanks to the positive evolution of the economy and availability. Seeing the evolution of prices of components such as nickel and cobalt, vehicles with LFP batteries are increasingly being chosen. There are several alternatives to try to achieve different objectives. A more economical way would be to replace Li^+ with Na^+ (Na-ion batteries). Another possibility for improvement would be Li-S batteries due to their performance. This type of battery has a greater energy capacity, favoring high efficiency. To focus on the possibility of evolution towards the change from combustion vehicles to implementing lithium batteries in electric vehicles, it is necessary to take into account electrochemistry, sustainability, the possibility of obtaining essential materials for their production and above all the cost they would have on the market.

Keywords: NCM batteries, LFP batteries, Li-polymer batteries, Na-ion batteries, Li-ion batteries.

2. RESUM

Els cotxes convencionals de combustió són un problema per causa de les grans emissions de CO_2. S'ha calculat que una quarta part de diòxid de carboni emès per activitats humanes prové dels vehicles de transport. L'objectiu és la descarbonització dels vehicles electrificant-los amb l'ús de bateries de liti com a font energètica que permeti la seva mobilitat per poder evolucionar cap a un futur més sostenible. L'anàlisi bibliogràfica mostra els diferents tipus de bateries de liti que poden ser útils en vehicles i la previsió de l'evolució segons els diferents escenaris, costos, materials disponibles i prestacions. Les bateries de ió-Li són les més utilitzades actualment i varien segons la composició del càtode. Les més destacades actualment són les NMC (níquel-manganès-cobalt) i les LFP (fosfat de ferro-liti). També hi ha altres tipus de bateries de liti que s'usen menys com les Li-polímer, una de les opcions que s'usa en alguns vehicles elèctrics lleugers. Les tecnologies emergents i les innovacions són claus per desenvolupar bateries de ió-Li amb materials que puguin millorar el consum gràcies a l'evolució positiva de l'economia i la disponibilitat. Veient l'evolució de preus de components com el níquel i el cobalt s'opta més per vehicles amb bateries LFP. Hi ha diverses alternatives per intentar assolir diferents objectius. Una via més econòmica seria substituir Li^+ per Na^+ (bateries ió-Na). Una altra possibilitat de millora serien les bateries Li-S degut a les seves prestacions. Aquest tipus de bateria tenen una capacitat energètica major, afavorint una eficiència elevada. Per enfocar la possibilitat d'evolució cap al canvi de vehicles de combustió a implementar bateries de liti en vehicles elèctrics és necessari tenir en compte l'electroquímica, la sostenibilitat, la possibilitat d'obtenir materials essencials per la seva producció i sobretot el cost que ocuparien en el mercat.

Paraules clau: Bateries NMC, bateries LFP, bateries Li-polímer, bateries d'ió-Na, bateries d'ió-Li.

3. Introduction

3.1. VEHICLES IN CIRCULATION AND POLLUTION

According to the International Organization of Motor Vehicle Manufacturers (OICA), there are currently more than 1.4 billion vehicles in the world. The high number of vehicles affects the environment, a quarter of global CO_2 emissions come from transport. To minimize climate effects, the electrification of vehicles is promoted; there are currently 58 million electric vehicles, including Battery Electric Vehicles BEVs (the most common) and Plug-in Hybrid Electric Vehicles PHVEVs. [1][2][3]

3.2. BATTERY BASICS

Batteries have as their main function the storage of chemical energy in order to convert it into electrical energy. This procedure occurs through electrochemical reactions. The battery is made up of different compartments and components (Figure 1 and Table 1).

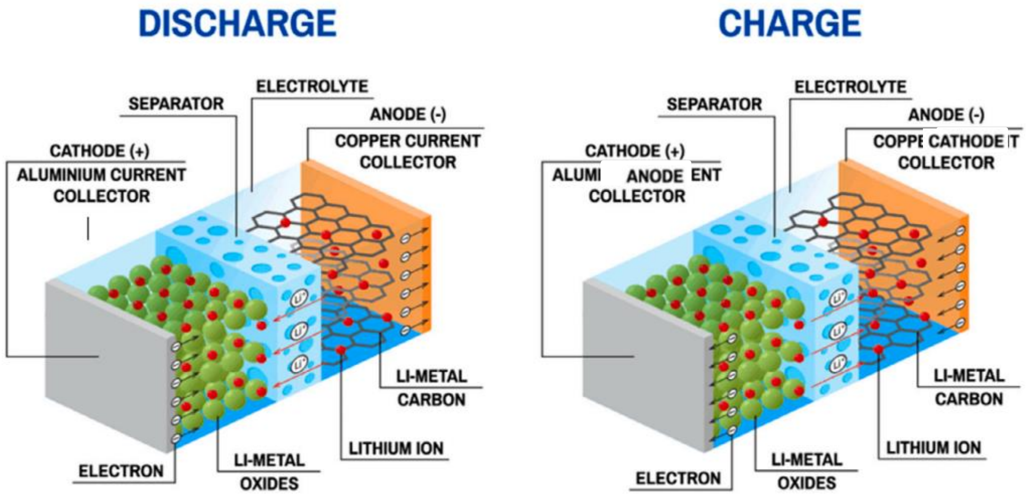

Figure 1: Charging and Discharging Process of Li-ion Batteries. Source: Image Credit: https://sivVector/Shutterstock.com [4]. Note that the cathode during the discharge becomes the anode when charging. However, we normally refer to the electrode that acts as the cathode during discharge as the cathode of the lithium battery. This will always be the positive electrode (pole) of the cell, both during charging and discharging.

Basic battery components	Function
Cathode	Positive electrode where the reduction process occurs.
Anode	Negative electrode where the oxidation process occurs.
Electrolyte	Liquid or solid medium through which ions move between the electrodes (anode and cathode) in the charging and discharging process.
Separator	Prevents short circuits by ensuring that the electrodes are not in direct contact, providing safety to the battery. Allows the passage of ions.

Table 1. Function of basic battery components. [4]

3.2.1. Basic definitions

To understand the performance of lithium batteries, it is necessary to introduce the definitions given in Table 2.

Key concepts	Definition	Impact
Energy density	Amount of energy that can be stored per unit volume (Wh/L) or mass (Wh/kg).	At a high energy density, batteries are light and compact, providing good autonomy.

Power density	Ability to provide high energy within a short time frame per unit volume (W/L) or mass (W/kg).	Allows fast charging.
Capacity	Amount of total electric charge that can be stored in a battery (Ah).	Energy provided in each time.
Energy efficiency	Relation between extracted energy and energy used to charge a battery.	At high efficiency the battery suffers less energy loss.
State of charge (SOC)	% of energy remaining with respect to maximum energy.	100% indicates that the battery is fully charged.
State of Health (SOH)	Battery status compared to when new.	100% indicates that the battery has not lost its original properties (maintains its capacity and efficiency).
Nominal Voltage	Average value of the cell potential in a discharge process.	In lithium batteries it is 3.6 to 3.7 V/cell.
Internal resistance	Opposition to the natural flow of the battery itself.	At high internal resistance the efficiency and performance of the battery are lower.
Thermal range	Temperature interval at which the battery remains efficient.	Temperature outside the appropriate range can cause damage to the battery.
Conductivity	Capacity to allow the movement of ions (ionic conductivity) or electrons (electron conductivity).	At a high conductivity the performance of the battery is greater.

Table 2. Main definitions.

3.2.2. Charging and discharging process in lithium batteries

The operation of batteries consists of storing chemical energy in the charging process and releasing electrical energy in the discharging process. In **the charging process**, when the battery is connected to an external power source, Li^+ is released from the positive electrode and passes through the electrolyte to the negative electrode. The associated electrons go from the positive to the negative electrode through an external circuit. The Li^+ remains within the structure of the negative electrode, stored until the discharging process. During **the discharge process,** energy is released, powering the device. Li^+ moves from the negative to the positive electrode through the electrolyte, and the electrons move from the negative to the positive electrode through the external circuit. [4]

3.2.3. Nernst equation and EMF in batteries

To determine the performance of batteries, one must know their cell potential, considering the concentrations of the components that determine the products and reactants. This potential is calculated using **the Nernst equation**. The **EMF** is calculated using the Nernst equation, as it determines the energy per unit charge that a battery supplies to move electrical charges in a circuit. As the battery reactants are consumed, the cell voltage decreases, and the products are generated. The EMF under standard conditions equivalent to the standard cell potential (E^o), but if the conditions were not these, the EMF would depend on the concentrations of the products and reactants, as indicated in Eq. (1). [5]

$$E = E^o - \frac{RT}{nF} ln(Q) \quad (1)$$

E: Electrode potential under non-standard conditions.

E^o: Electrode potential under standard conditions

R: Ideal gas constant

T: Temperature

F: Faraday's constant

Q: Reaction quotient of the cell reaction

3.2.4. Types of batteries

Batteries are classified into three groups: **primary, secondary and fuel cells**. The simplest battery is the primary battery, which is not rechargeable, has a limited lifespan and its chemical reaction is irreversible. The secondary batteries are rechargeable, with a long duration when recharging and with a reversible reaction. These batteries are the ones used in electric vehicles. Since this type of battery can store energy, it is also called accumulator. Finally, there is the fuel cell, which works using liquid or gases fuels, which are externally fed. These batteries are reused whenever there is a supply, therefore, the duration is unlimited as long as the fuel is available. They normally use a hydrogen tank and atmospheric oxygen. To understand the capabilities of primary and secondary batteries, their differences must be considered (see Table 3). [6]

Features	Primary batteries	Secondary batteries
Reusability	Single use	Rechargeable
Performance and capacity	Large initial capacity and more stable discharge process.	Large initial capacity, but performance is affected by charge-discharge cycles.
Applications	Devices with low energy demand and that do not require recharging (e.g. watches, flashlights).	Devices that are used frequently (e.g. electric vehicles, mobile devices, laptops).
Environmental impact	Difficult to recycle, thrown away after use.	Less environmental damage in the long term.
Cost	Cheap	High initial cost, but cost-effective over time as they can be recharged.

Table 3. Features of primary and secondary batteries

On the other hand, we have the **fuel cells**. These are considered for their **environmental impact** and the applications they can provide. This type of battery has efficiency and **degradation problems** causing irreversible losses. In the case of the transport sector, hydrogen fuel cells provide emission-free mobility and a fast-charging time. One of the characteristics similar to conventional batteries is that they can be rechargeable, although their development is slower. [7]

3.3. BATTERY PERFORMANCE

In order to achieve high efficiency in Li batteries for the different applications, power optimization must be taken into account. The maximum power point allows a balance to be achieved, preventing overheating and achieving good performance. Figure 2 shows the typical form of the discharge voltage (V) and of the power density (P) in front of the current density (j).

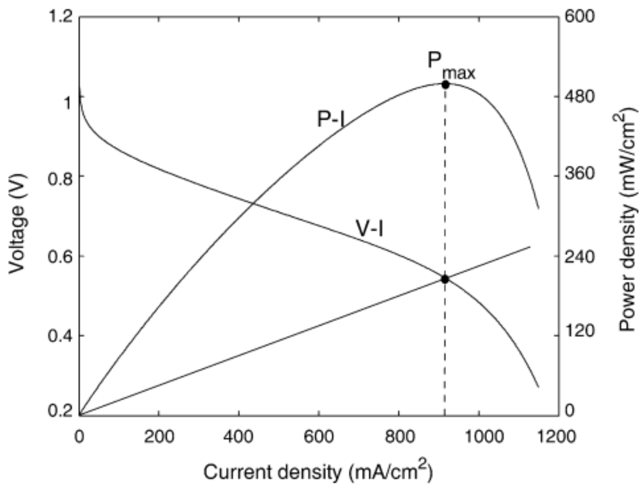

Figure 2: Graph of current, power and voltage of a cell [8]

3.3.1. Voltage of the battery

The function of the lithium battery is to provide energy. During the supply, the voltage decreases, and the current intensity increases. This is explained by the equation (**2**). **k** is linear extrapolation constant of voltage as a function of current, R_{int} is the internal resistance, and **I** is the current intensity.

$$V = k - IR_{\text{int}} \quad (2)$$

When the current intensity is low, the voltage is similar to that of the open circuit. **When the current intensity increases**, the voltage drops significantly due to the internal resistance of the battery. **If the current intensity is very high**, the voltage decreases drastically affecting the performance of the system. [8]

3.3.2. Power of the battery

Equation (**3**) indicates the electrical power supplied by the battery. The power depends on the current intensity. Initially, when the current intensity increases, the power also increases, but when it reaches a maximum value, it decreases again due to internal losses. To determine the maximum power point, Equation (**4**) is derived by setting it to 0. As a solution to the derivation, we obtain Equation (**5**). The result obtained indicates that when the internal resistance of the battery increases due to damage or aging, the optimal current decreases. The value of Imp is important. **The system must operate at a smaller current intensity than that of the** Imp to provide adequate battery efficiency.

$$P = VI = I(k - IR_{\text{int}}) \quad (3)$$

$$dP/_{dI} = k - 2IR_{\text{int}} = 0 \quad (4)$$

$$I_{\text{mp}} = k/2R_{\text{int}} \quad (5)$$

The **V-I curve is divided into three different zones**. The first part corresponds to **the activation polarization zone**, the voltage gradually decreases with the increase in current due to the activation losses produced to drive the chemical reactions to produce energy. The second part corresponds to **the ohmic polarization zone**. The decrease in voltage when providing current is almost linear. This decrease is due to resistance losses due to the charge transport resistance. Finally, there **is the concentration polarization zone**, where a sudden decrease in voltage is seen in relation to a high intensity due to the mass transport control. In this last section the reactants do not reach the electrodes with sufficient speed. [8]

3.4. ORIGIN OF LITHIUM BATTERIES

Lithium batteries have a history of development and evolution. Electrochemical studies began with lithium after its discovery, and today it is one of the possible solutions to improve technological aspects, making our lives easier and contributing to the evolution towards a more sustainable world.

3.4.1. First research on Li

Lithium was discovered in 1817 by scientists Arfwedson and Berzelius analyzing the mineral petalite ($LiAlSi_4O_{10}$). After a century, the chemist G.W. Lewis began studying its electrochemical properties. He concluded that it could be a great candidate as an anode material thanks to its low density and high specific capacity.

In 1958, lithium was studied in batteries, focusing his research and experimentation on its electrochemical properties. Harris determined the stability of lithium batteries by checking the solubility of lithium in different types of electrolytes. It was observed that no direct chemical reaction occurred between **the propylene carbonate electrolyte** and lithium, but there was transport of Li^+ ions. This showed that it would be an organic solvent suitable as an electrolyte because it would not produce problematic reactions in batteries in the future. [9]

3.4.2. Advances in the development and commercialization of primary and secondary Li batteries

The first primary lithium batteries were commercialized in the late 1960s. These batteries were notable for their long lifespan and high energy density in small devices. In 1969, the lithium sulphur dioxide battery (Li/SO_2) appeared on the market, followed by the lithium–polycarbon monofluoride battery (Li/CF_x) in 1973 and the lithium–manganese oxide battery (Li/MnO_2) used in rechargeable solar calculators in 1975. [37]

In 1970 M.S.Whittingham introduced the development of rechargeable lithium batteries, discovering that it was possible to manufacture them using **TiS_2 as the cathode material and metallic Li as the anode material**. Thanks to this breakthrough, the first lithium battery was commercialized in 1978, launched by the EXXON company in the United States. It was found that the battery had certain **safety problems** due to the reactivity of metallic lithium. The reactions given in Table 4 correspond to the charging and discharging process of TiS_2/Li battery. [9][10]

	Charge process	Discharge process
Reaction at the positive electrode	$LiTiS_2 \rightarrow TiS_2 + Li^+ + e^-$	$TiS_2 + Li^+ + e^- \rightarrow LiTiS_2$
Reaction at the negative electrode	$Li^+ + e^- \rightarrow Li$	$Li \rightarrow Li^+ + e^-$
Global reaction	$LiTiS_2 \rightarrow TiS_2 + Li^+$	$TiS_2 + Li^+ \rightarrow LiTiS_2$

Table 4. Reactions of TiS_2/Li battery.

3.4.3. Important innovations

The study of cathode and anode components are what have made lithium batteries evolve. In 1980, the **development of the $LiCoO_2$ cathode** by John B.Goodenough occurred, improving stability and providing an increase in energy density. Only three years later, Rachid Yazami determined that **the appropriate material for the anode was graphite**, since it was safer than metallic lithium. These two scientists are the ones who drove the main characteristics of the lithium batteries that we know today. [10]

3.4.4. Commercialization and development of LFP, NMC and NCA cathodes.

The first lithium-ion battery to be commercialized was in 1991 with improved properties over previous technologies. Later, in 1996, John Goodenough developed the **cathode with $LiFePO_4$** in order to acquire key characteristics such **as thermal stability, safety and the proportion of a long useful life**. This type of battery was the first applied to electric vehicles. [10]

From 1990 onwards, more advanced cathodes were developed for applications and for the operation of more modern electric vehicles. These are cathodes such as **NMC** (Nickel Manganese Cobalt Oxide) and **NCA** (Nickel Cobalt Aluminum Oxide) with a structure that allows the intercalation of Li^+. Both cathodes provide a high energy density and adequate power for the operation of electric vehicles. Currently, there is promising research to improve the most relevant properties, experimentation is being carried out in solid-state batteries (batteries with solid electrolytes), which stand out in safety and high energy density and in changes in the anode using silicon to improve energy storage capacity, since silicon can store more Li^+ ions than graphite. Figure 3 shows the evolution of the chemical Li-ion batteries over the years.[10][11]

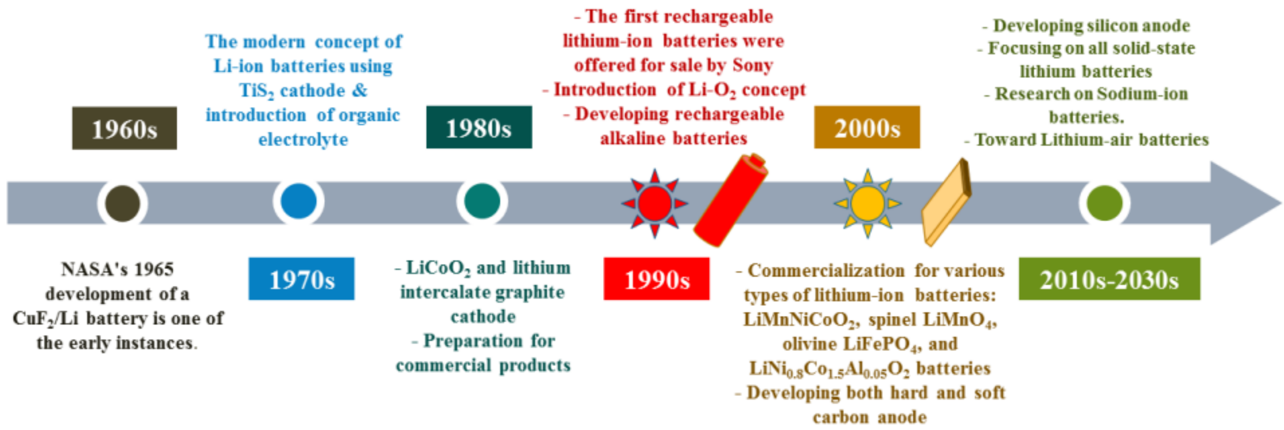

Figure 3: Chemical Li-ion batteries over the years. [11]

3.5. LOW AND HIGH SCALE APPLICATIONS OF LITHIUM BATTERIES

Lithium batteries are used in different sectors providing a multitude of applications thanks to their flexibility in power and energy. These can be used both in less complex applications and in larger applications that require more capacity, high power and great safety to be efficient during their useful life. In small applications, the aim is to offer energy within a limited space. This sector includes consumer devices, medical devices such as pacemakers.[12]

Features	Small applications	Great applications
Weight and size	Compact and light (few grams)	Bulky and heavy (from kilograms to tons)
Design of cells	Individual cells	Many cells connected in series
Energy density	Hight	Very hight
Battery Management System (BMS)	Basic	Complex
Thermal management	Thermal dissipation is not a concern	Advanced BMS systems
Capacity	Average	Hight
Cost	Economic	More expensive
Service life	Average	Very long

Table 5. Features of small and great applications.

The different characteristics of lithium batteries focus on the objectives of each type of application. The weight of the batteries in small applications must be light to provide comfortable portability, on the other hand, in large applications they are heavier to be able to store much more energy. In the case of the design of the cells it is more complex, since for industrial devices and electric vehicles cooling systems are needed, sensors to monitor each cell and structures with materials that provide high safety. Cooling and ventilation systems are important to avoid overheating, increase the useful life by making there are fewer failures during their operation. Small applications do not need a construction that requires a cooling system, which makes it have a simpler design. The cost is more expensive in large-scale applications due to the type of materials used and the technology implemented.[12] [13]

4. OBJECTIVES

The general objective of this bibliographic analysis is the current study of the use of lithium batteries in electric vehicles and analyze the proposals of technologies to determine their future. This research includes the following purposes:

- Study the operation, the fundamentals of electrochemistry with respect to batteries, the main characteristics of lithium batteries and the chemical composition of the most used (NMC, LFO) and the least used (Li-Polymer).
- Analyze the cost of lithium batteries to understand what decisions must be made for their development and production.
- Search alternatives to the current Li-ion batteries.
- Analyze global policies for a positive energy transition for the environment by producing batteries that are sustainable and efficient at the same time.
- Analyze how to contribute to the decarbonization of vehicles in the transport sector and evolve towards a more sustainable planet.
- Determine the short and long-term evolution of lithium-ion batteries and other alternatives, such as sodium-ion batteries or batteries with a silicon anode component.

5. METHODS

The information collected for the bibliographic analysis carried out was extracted from several databases (Table 6). The search was carried out between 19/02/2025 and 24/06/2025.

Database	Search type
Web of Science	Search for reviewed articles related to science addressed to the lithium battery sector and its most relevant applications to analyse the current vision in the related technologies.
Google Scholar	Search for scientific articles, technical reports and data from international conferences although some documents must be reviewed to ensure their reliability.
SciFinder	Search for publications related to science and technology. Focuses on a deeper and more specific search.

Table 6. Types of research in different databases.

To conduct an adequate research, searches have been made focused on different keywords and more specific aspects in relation to lithium batteries and alternatives for different applications and electric vehicles. The **most used keywords** are among others Li-ion batteries, environmental impact of batteries, innovations in electric vehicles of lithium batteries, basic components of batteries, cathode materials of lithium batteries, anode materials of lithium batteries, types of separators, types of electrolytes, crystal structure of components of lithium batteries, sodium ion batteries, Li-S batteries, solid state batteries and battery innovations.

In relation to **the temporal filters**, the articles, journals, web pages or documents searched have been limited to different time intervals. In the case of the topic of present studies and future innovations, articles have been searched between 2015 and today. In 2015, the purposes of the 2030 agenda were published and, therefore, innovations in lithium batteries in electric vehicles and their regulations should be seen in documents from 2015 onwards. In terms of basic concepts and history in relation to lithium batteries, the publication time of the articles consulted has been wider.

In the case of the default **language** in the search for information, it has been done in English because it has a large presence in scientific and technological documents in all the databases consulted. Searches have also been made in Spanish in some specific area, generally in the Google Scholar database.

Unreliable sources of information have been excluded, such as blogs or some websites that do not provide information relevant to the research topic.

Often, to complement the research, examples have been sought in the **ChatGPT artificial intelligence**. The information found has subsequently been counterbalanced in reliable articles found in the databases mentioned in Table 6.

6. RESULTS AND DISCUSSION

6.1. MATERIALS IN THE CONFIGURATION OF LITHIUM BATTERIES

6.1.1. Cathodes that make up Li batteries

The cathode is one of the important parts that make up lithium batteries, since depending on the materials that constitute it will determine the influence on the useful life, energy density and stability. The composition of the cathode determines the safety, storage capacity and degradation rate of lithium batteries. The most commonly used cathode materials for lithium batteries are **LCO** (Lithium Cobalt Oxide) **LFP** (Lithium Iron Phosphate), **NMC** (Lithium Nickel Cobalt Manganese Oxide), **LMO** (Lithium Manganese Oxide) and **NCA** (Lithium Nickel Cobalt Aluminium Oxide). Table 7 shows the advantages and disadvantages of each type:

Cathode material	Advantages	Disadvantage
$LiCoO_2$ (LCO)	High energy density Good stability in charge/discharge cycles	High cost Short lifespan Unsafe
$LiFePO_4$ (LFP)	Long service life Low cost High safety High thermal stability	Low energy density Low voltage
$LiNiMnCoO_2$ (NMC)	Good balance between lifespan, energy density and safety Good performance, depends on the proportion of the elements that constitute it.	High cost
$LiMn_2O_4$ (LMO)	Good balance between safety, specific power and useful life.	Low overall performance
$LiNiCoAlO_2$ (NCA)	High energy density More thermally stable than NMC	High cost Unsafe in extreme conditions

Table 7. Material cathode [14]

Table 7 indicates that NMC and NCA cathodes, having a high energy density, provide high performance. LFP cathodes are used to prioritize safety and sustainability. In the case of LCO, although it has a high energy density, it is not used in many cases due to its large size and low availability. The best option to replace this type of cathode in large-scale applications is NMC with a low cobalt ratio. On the other hand, the LMO cathode is used in applications that require good thermal stability and high power. The disadvantage of this type of cathode is that it is not useful in applications that require high energy density.[14]

6.1.1.1. Comparison of the potential and the specific capacity of the cathode in lithium-ion batteries

The cathode material largely determines the performance of lithium batteries due to its great influence on the stability of the system, the potential and the specific capacity. Depending on the composition of the cathode, it affects in one way or another the amount of energy that can be stored and the efficiency at the same time of the supply of this energy. The differences can be seen in Figure 4 of the specific capacity for the different cathode materials used in lithium batteries. In Figure 4 the curves are divided into three different zones. The first zone indicates the start of the lithiation of the cathode, that is, the insertion of Li^+ ions into the crystalline structure of the cathode material. In this first part of the curve there is a voltage loss because at the beginning the insertion of lithium ions is difficult due to the oxidation states of the transition metals that constitute the cathodes. In the intermediate zone the intercalation reaction occurs in a steadier form. At this point in the graph the curve is more stable because the insertion is controlled. Finally, a steep downward slope of the potential is observed. In this zone, the cathode is saturated with Li^+ ions and the maximum useful capacity of the cathode is reached. [15]

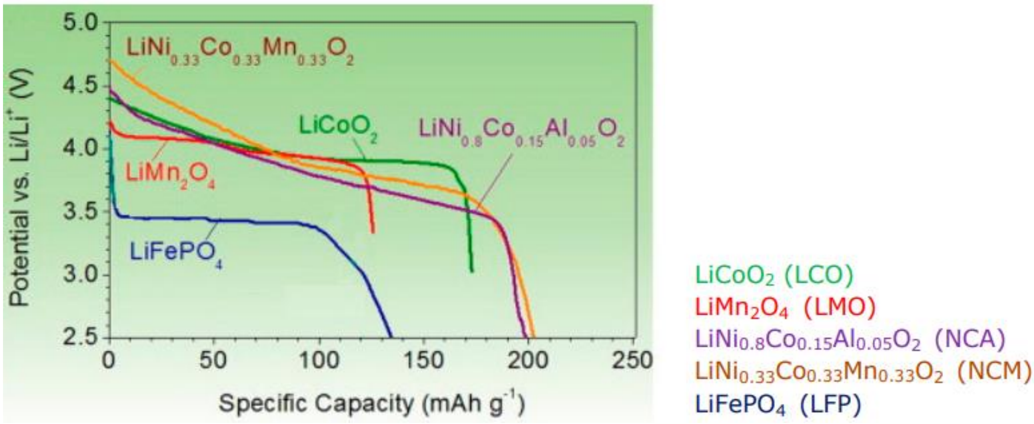

Figure 4: Graph of the electrode potential of cathode materials in lithium batteries vs specific capacity. [15]

Depending on the cathode material used, the electrical potential varies in a way that allows the voltage in the discharge process to be determined. LCO has a potential established between 3.8 and 4.2 V and a specific capacity of approximately 145 mAh/g. In the case of LFP, the potential is 3.4 V and the specific capacity is similar to that of $LiCoO_2$, and the specific capacity is similar to that of $LiCoO_2$, which tells us that the energy per unit of discharge stored is lower. The cathode composed of $LiMn_2O_4$ has a voltage of 4V and a lower specific capacity (110-120 mAh/g) and its discharge curve is steeper. NMC has a high specific capacity (180-200 mAh/g) for a voltage in the range of 3.7-4.2 V. This fact indicates that its energy density is higher than LCO and LMO. Finally, NCA is the one with the highest specific capacity in relation to voltage 200-220 mAh/g for a voltage of 4.2 V, therefore, it is the one that stores the greatest charge.

NCA and NCM materials have a higher voltage than other cathode components and have a higher energy per unit charge. LFP has a lower voltage but is more stable in the discharge process. NCA and NCM cathode materials are the ones that store the most charge due to their high specific capacity.[15]

6.1.1.2. Crystalline structure of cathode materials in lithium batteries

The influence on the performance of lithium-ion batteries also has to do with the different crystal structures of the materials that make up the cathode. Figure 5 shows the different structure for cathode materials. **The LCO, NCA and NMC** cathodes have a **laminar structure** that allows the mobility of lithium ions. The only difference between the three cathodes is the proportion of the elements. The NMC has a proportion of nickel, cobalt and manganese. This composition allows for an improvement in the balance between stability, price and performance. The NCA has a large predominance of nickel, which allows for an improvement in energy density compared to the LCO. In the case of the cathode material formed by **LMO**, it has a **spinel structure** that allows a fast charge/discharge process and a more favourable mobility of lithium ions. Finally, **the structure of the LFP is olivine**. This crystal structure allows for higher safety and thermal stability.[16][17]

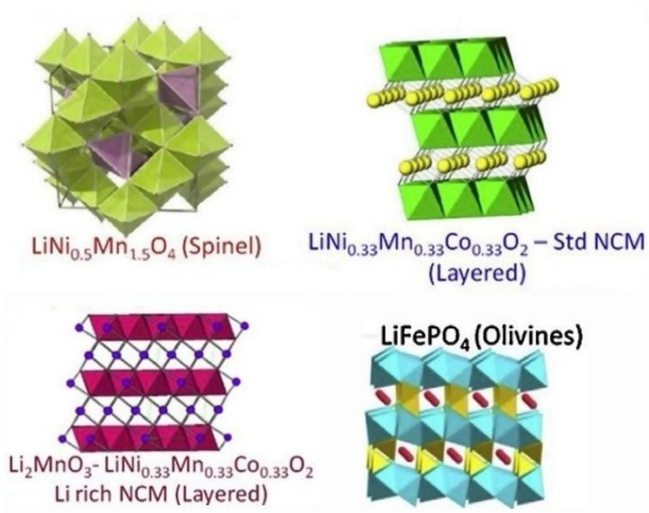

Figure 5: structure of cathode materials of lithium-ion batteries [17]

6.1.2. Anodes that make up Li batteries

The most commonly used anode materials include **graphite**, **transition metal oxides** such as **MnO** and **LTO**, **silicon** and **alloys** (see Table 8).[18]

Anode material	Advantages	Disadvantage
Graphite	High electronic conductivity Stable structure Low cost	Low-rate capacity Low specific capacity Not so safe under certain conditions
Silicon	High specific capacity Low cost Abundant	Very large volumetric expansion (300%)
Alloy	High specific capacity High safety	High volumetric expansion (100%) Low electronic conductivity
Transition metal oxides	Very high specific capacity Does not suffer from volumetric expansion	Low Coulombic efficiency High potential hysteresis

Table 8. Material anode [18]

The most widely used material today due to its structural stability, good electrical conductivity and cost is graphite. However, it has a low-rate capacity (low performance due to limited capacity in fast charging and discharging processes) and low specific capacity.

Transition metal oxides have good capacity, safety and a long useful life. The high potential hysteresis of transition metal oxides causes voltage differences in the charging and discharging process that cause energy losses. MnO has low toxicity and good stability, but its conductivity and capacity are not as good. Alloys and silicon have a great storage capacity, although they have problems in charging/discharging processes due to volumetric expansion.

Silicon is a promising anode material for Li-ion batteries. This anode component is not used in its metallic form due to problems of volumetric expansion and possible degradation. The types of silicon indicated in Table 9 are those most used in experimental or commercial phases.

Different forms of Silicon in the anode	Structure	Features	Current state
Silicon + Graphite (Si/C) [19]	Hybrid (partially amorphous) Silicon nanoparticles in a carbon matrix	Good conductivity Long service life Improves volumetric expansion problems	Low-scale commercial
Amorphous Silicon (a-Si) [20]	Amorphous	Good coulombic resistance (good efficiency in the charging and discharging process over many cycles) Improves volumetric expansion problems	Experimental
SiOx compounds [19]	Generally amorphous	Good balance between storage capacity, lifespan and energy density	Commercial
Silicon nanoparticles [21]	Partially amorphous with diamond-like structure	It reduces the chance of degradation and improves the useful life.	Experimental

Table 9. Types of Silicon forms in anode

6.1.2.1. Comparison of the potential and the specific capacity of the anode in lithium-ion batteries

Both cathode and anode materials determine the efficiency, capacity and stability of lithium batteries. The figure 6 shows **the comparison of different anode materials** in terms of potential and specific capacity.

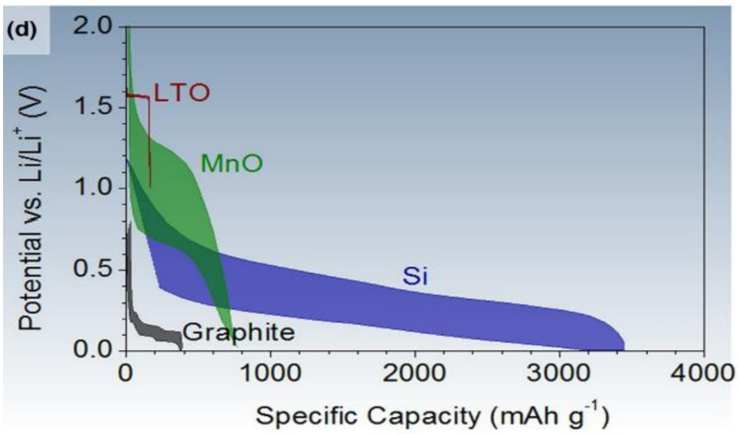

Figure 6: Graph of the electrode potential of anode materials in lithium batteries.[16]

Graphite has a low specific capacity, approximately 350 mAh/g, at a relatively low potential (0.1-0.2 V) which allows for a long useful life and adequate stability. The specific capacity of silicon is approximately 3500 mAh/g, significantly exceeding that of graphite, making charge storage greater. MnO has an average specific capacity (800-1000 mAh/g). $Li_4Ti_5O_{12}$ (LTO) has a potential of 1.5 V and a low specific capacity, making it not useful in applications that have a high energy density. [16]

6.1.2.2. Crystalline structure of anode materials in lithium batteries

The crystalline structure in the anode must be suitable to avoid problems such as short circuits and dendrite formation in lithium-ion batteries. The structure must allow the insertion and extraction of lithium ions efficiently in the charging/discharging process. The correct composition and organization of the atoms makes the storage capacity better and the batteries last longer. Each type of anode has a certain crystalline structure according to Table 10.

Anode material	Crystallographic structure
Graphite	Laminar hexagonal structure
$Li_4Ti_5O_{12}$ (LTO)	Spinel
Silicon	the structure depends on the silicon alloys
Alloy	Hybrid combination

Table 10. Crystalline structure of anodic materials [22]

Figure 7 shows structure of different anode materials. The crystalline **structure of layered graphite** makes the insertion of lithium ions favorable. **LTO** is stable and does not suffer from deformations thanks to **its spinel structure**. Alloying lithium with silicon makes the volumetric expansion smaller. Analysis of the crystal structure of anode materials shows that graphite and LTO are stable but have low capacity. On the other hand, they show that silicon and its alloys have higher capacity but have the problem of volumetric expansion. [22]

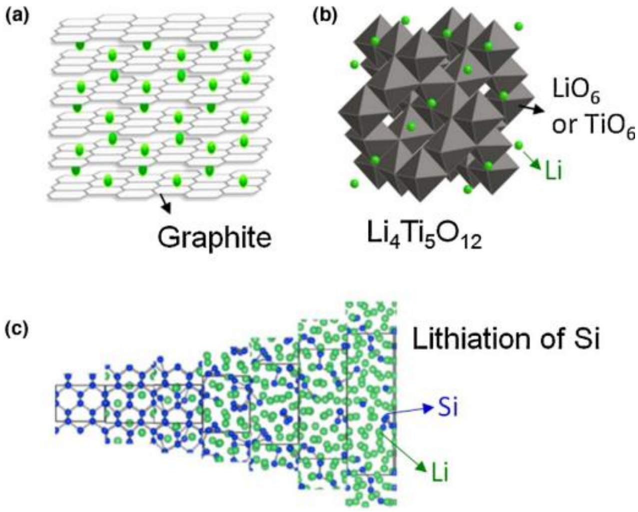

Figure 7: Strucure and lithiation of different anode materials [16]

6.1.3. Electrolytes in Li-ion batteries

There are different types of electrolytes: **liquid, solid and polymeric**. The most widely used electrolytes are liquid due to their high conductivity although they have problems related to flammability. These electrolytes are composed of lithium salts in organic solvents. Solid electrolytes have limited conductivity but are safer and resistant to the formation of dendrites. On the other hand, polymeric electrolytes are more flexible and safer although there are problems related to ionic conductivity and performance at high temperature. Table 11 shows different types of electrolytes that normally uses in batteries. [23]

Types of Electrolytes	Advantages	Disadvantage	Examples
Organic Electrolytes	Good efficiency and performance Promotes the dissolution of lithium salts	Low safety Volatility problems	$LiPF_6$, EC, FEC i DMC
Aqueous Electrolytes	Low cost Environmentally friendly High conductivity at low temperatures	Low stability at high voltages Electrode corrosion	$LiSO_4$, LiOH, LiF
Solid Electrolytes (SE)	High safety High energy density Thermally stable	High production cost Complexity in manufacturing processes	$LiTaO_3$, $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$
Solid Electrolyte Interface (SEI)	Prevents the formation of dendrites Stable and provides durability	Unstable under some load conditions	EC, $LiFePO_4$
PVDF-Based Electrolyte	High stability Good ionic condition	Complex manufacturing	PVDF, PVDF-HFP, PEO
Polymer Gel (GPE)	Safe Thermally stable	Complex manufacturing	PVDF-HFP, PEO-LiTFSI, PVA-$LiClO_4$
Ionic Liquid Electrolytes (IL)	Good stability at high temperature High conductivity Safe	High cost Difficult handling in large quantities	PYR14TFSI, LiTFSI
Polymer Electrolytes (SPE)	High flexibility Safe High performance over a wide temperature range	Low conductivity at low temperature	PVDF/PEO, PVDF-HFP

Table 11. Types of electrolytes [23]

6.1.4. Separators in Li-ion batteries

The function of **separators** is to separate the electrodes by means of a porous and inert physical barrier that allows the passage of ions during the charging and discharging process. Separators prevent short circuits by keeping off direct contact between the cathode and the anode. In order to meet these characteristics, the properties explained in Table 12 must be taken into account.[24]

Separator Properties	Explanation
Stability	It must be inert. It must not be electrically conductive so as not to cause short circuits.
Porosity	It must have approximately 40% porosity to allow the passage of ions. It is important that the pores are smaller than the active components.
Thickness	It must be thin (approximately 25 µm).
Wettability	It must be "soaked" with electrolyte.
Permeability	The pores must be smaller than the components that form the cathode and anode to prevent the passage of unwanted compounds.
Thermal Shear	For greater safety, the separator must be sealed before the "thermal runaway".
Cost	The cost must be low.
Mechanical Strength	It must be mechanically stable so as not to break in the battery manufacturing process.

Table 12. Important characteristics of separators [24]

There are three types of separators for Li-ion batteries focused on electric vehicles: **microporous polymeric, nonwovens, and ceramic composites**. Table 13 shows examples of the mentioned separators and the most important characteristics of each type. [25]

Separator Classification	Features	Examples
Microporous Polymer	Shutdown function providing thermal safety When PE melts at 130°C, the passage of ions is blocked, preventing fires.	Polypropylene/Polyethylene/Polypropylene (PP/PE/PP)
Non-woven	Composed of fibers Very porous Good absorption of electrolyte Withstands temperatures up to 200°C	Polyimide (PI) Polyethylene Terephthalate (PET) Polyacrylonitrile (PAN) Polyetherimide (PEI) Polybenzimidazole (PBI)
Ceramic Composite	High safety Retains electrolyte well Resistant to high temperatures	Alumina-coated separator (Al_2O_3) Zirconia-coated separator (ZrO_2) Silica-coated separator (SiO_2)

Table 13. Types of separators [25]

6.2. APPLICATIONS OF LITHIUM BATTERIES

Li-ion batteries have advantages that allow a fairly long scale of applications (see Table 14). Due to characteristics such as energy density and useful life, they are used in sectors such as **mobility, electronics and energy storage (Table 14)**. The development of Li-ion batteries is important in current and future applications to move towards a sustainable and efficient energy production system.

Mobility	Energy Storage	Electronics
Automotive	Renewable Energy	Mobile Phones
Heavy and light mobility	Industry	Electronic and Electrical Appliances
Charging infrastructure	Housing	Medical Devices

Table 14. Application sectors of Li-ion batteries [26]

Developing technologies to improve **mobility** leads us to a scenario with lower costs and higher performance. Lithium-ion batteries in the transport sector require charging points that are distributed appropriately for proper operation. In the case of mobility, this includes both cars and light mobility vehicles (electric scooters and bicycles) and heavy mobility (trucks, trains, ships and airplanes). In **the energy storage sector**, the administration of electrical current is offered for a prolonged period, and it can also be discharged many times. Within this block, the most used applications are in the areas of telecommunications, renewable energy systems (photovoltaics and wind energy), home security by creating alarms, ATMs Automated Teller Machine), power supplies and medicine. The evolution of new technologies means that the batteries of devices in **the electronics sector** are small and offer high energy density and good energy efficiency. Devices such as tablets, mobile phones, laptops, drones and medical devices are built. [26]

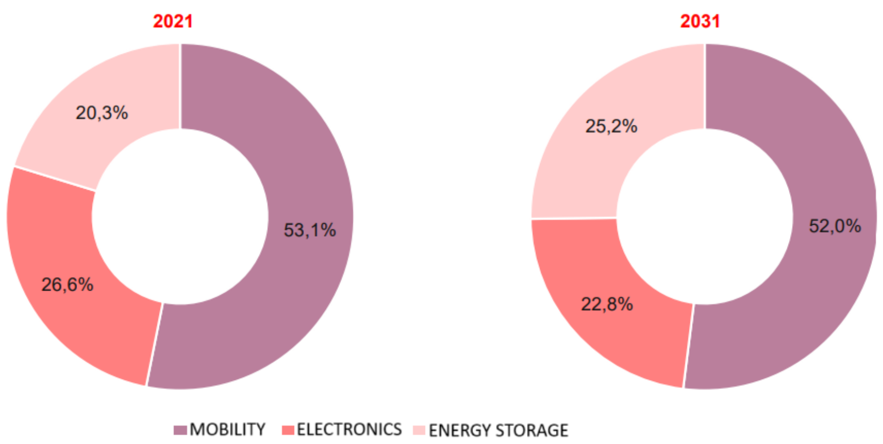

Figure 8: Applications in different sectors: 2021 vs 2031 forecast [26]

According to Figure 8, the **mobility** sector is the one that uses lithium-ion batteries the most now and in the future. Energy storage will grow from 20.3% to 25.2%, surpassing the electronics sector due to the use of renewable energies.[26]

6.3. BATTERIES APPLIED TO ELECTRIC VEHICLES

6.3.1. Most used batteries

Li-ion batteries are currently the most widely used in electric vehicles (Table 15). The chemical composition of each one determines its performance and applications.

Battery Type	Percentage of Use in 2022 (%) [28]	Percentage of Use in 2024 (%) [27]	Applications in Electric Vehicles
LFP	30	40	Commercial vehicles, electric buses and urban vehicles
NMC	60	48	High and mid-range vehicles
NCA	8	6	High-performance vehicles

Table 15. Types of batteries most currently used [28]

The use of lithium batteries depends on the different regions of the world. LFP batteries in the international market in 2024 were 40%, increasing compared to 2022 due to the increase in their commercialization in China. The rest of the market is mainly made up of NCA and NMC batteries. NMC batteries decrease slightly compared to 2022 due to the high demand for LFP batteries. NCA batteries are present in the market for high-end vehicles.[28] [27]

According to the distribution percentages of lithium-ion batteries in electric vehicles in other years, it can be deduced that if LFPs represent 40%, NMCs and NCAs represent 48 and 6% respectively. [27]

6.3.2. Battery structure in electric vehicles

Batteries in electric vehicles have a structure composed of cells, these are grouped into modules and are completed by a grouping of modules creating a battery pack (Table 16 and Figure 9). The shape of the structure allows weight distribution, space optimization and making it safer. [29]

Principal components	Description	Function
Cell	Individual energy storage unit	Store electrical energy
Modules	Cell grouping	Increases electrical energy storage capacity
Battery Pack	Module grouping	Manages security and supplies energy
BMS	Electronic system that manages the battery pack	Controls temperature, voltage and load for good efficiency

Table 16. Principal components of a battery [29]

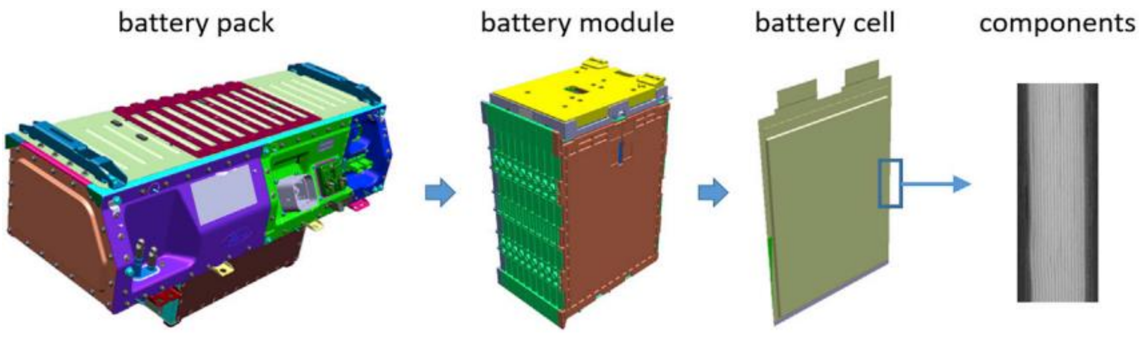

Figure 9: Battery composition in electric vehicles. [29]

Safety and efficient operation of electric vehicles are essential to prolong service life, improve performance, prevent battery damage, prevent overheating and improve performance. To achieve these characteristics, it is necessary to implement a battery management system (BMS) with the characteristics shown in Figure 10. [14]

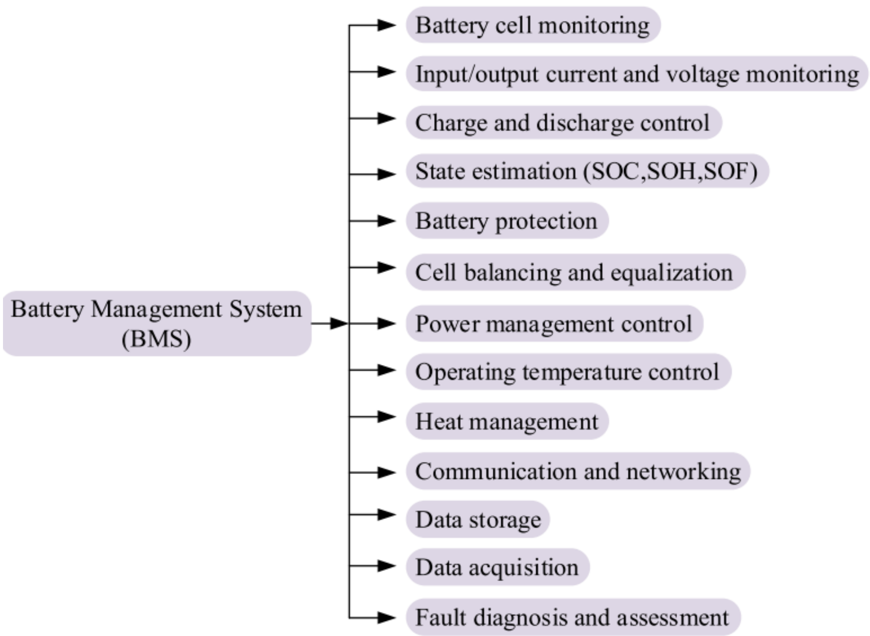

Figure 10: Description of BMS [14]

6.4. PERFORMANCE AND COST OF LITHIUM BATTERIES

6.4.1. Lithium-ion battery performance

The performance of lithium batteries determines the performance and correct operation of electric vehicles. The main performance is found in the table 17. [30]

Main features	Description	Typical values
Specific energy (Wh/kg)	Energy storage per kg of battery	90-180
Temperature in functioning (˚C)	Optimum temperature range for a battery to function properly	Ambient temperature
Charge/discharge efficiency (%)	Percentage efficiency in the charging/discharging process	90
Time to load (h)	Time to fully charge the battery	2-3
Number of life cycle	Number of times a battery can be charged and discharged before performance declines	Over 1000
Lifespan (year)	Durability of the battery	Over 7
Internal resistance (ohm)	Resistance that affects the efficiency of the charging/discharging process	Very low
Nominal voltage by element (V)	Nominal voltage per cell	3,6

Table 17. Main features of Li-ion batteries in electric vehicles. [30]

6.4.1.1. Charging and discharging characteristics in a Li-ion battery

To analyze the electrochemical behavior of Li-ion batteries, the curves that explain the behavior in the charging and discharging processes must be studied. In Figure 11a it is observed that **the charging current** is constant at the beginning of the process and that the **voltage** increases progressively in the interval of **(2.9-4.0) V approximately**. When the voltage reaches the maximum point, the charging current decreases until reaching the value of 0. At the same time of these events, the **accumulated capacity** increases continuously until reaching full charge. This charging process is called **constant current-constant voltage control (CC-CV)**. Figure 11b represents the discharge process. It is observed that the **voltage decreases progressively** from **4.2 to 3 V** (minimum discharge voltage) when supplying energy. The current remains constant until reaching 1 A (maximum current). It is also observed that for this process **the delivered capacity is 6.5 Wh**, a value that indicates high energy efficiency. [14]

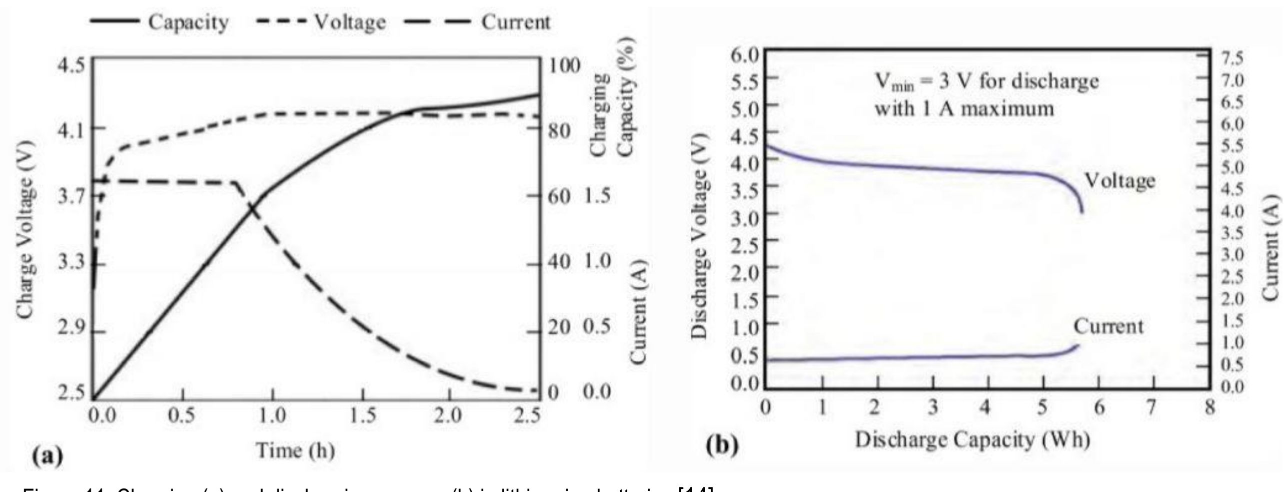

Figure 11. Charging (a) and discharging process (b) in lithium-ion batteries [14]

6.4.2. Lithium-ion battery market and costs

The demand for lithium-ion batteries is increasing exponentially due to the electrification of vehicles and the energy transition, from 500 GWh in 2018 to a forecast of 3000 GWh in 2030. China has been the leading consumer of lithium-ion batteries. In 2018, demand was 68.5% and it is expected to decrease to 42.8% in 2030. On the other hand, the United States and other countries are expected to increase their demand, causing the global market to expand. [31]

The price of lithium batteries has fallen significantly in recent years, and it is expected to fall even further with new technologies once they become available on the international market. The price of batteries has risen from $770 per kWh in 2013 and is expected to continue to fall to $64 by 2030 (Figure 12). [26]

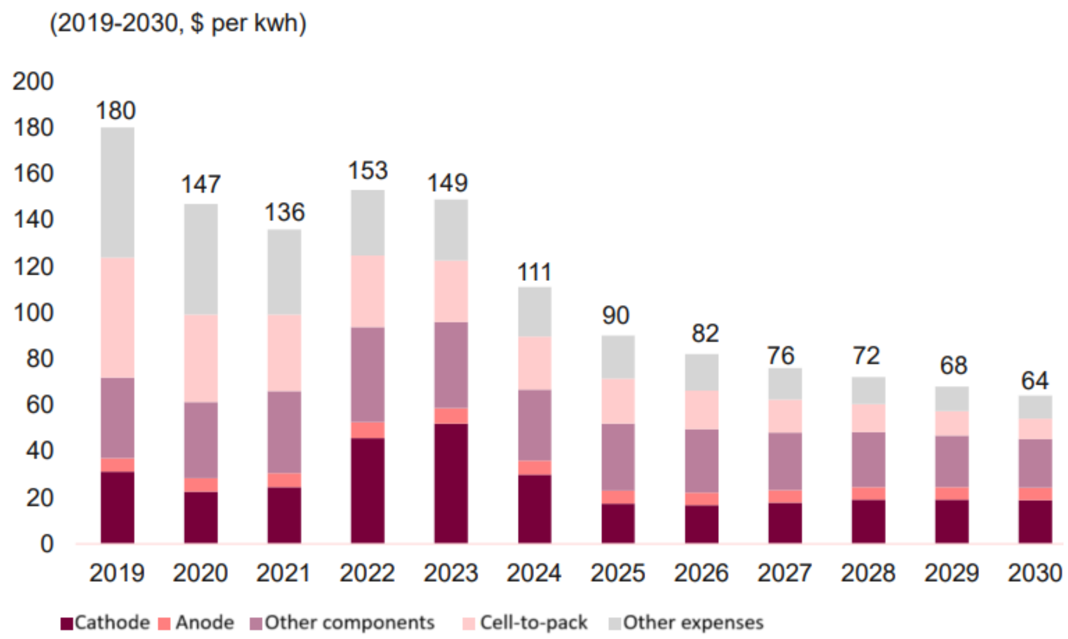

Figure 12: Li-ion battery costs from 2019 to 2030 [26]

The cost of Li-ion batteries depends, among other factors, on the cathode and anode materials. The **cathodes** with the **lowest costs** are **LMO** and **LFP**. The **most expensive** are **LCO, NMC and NCA** due to the high price of nickel and cobalt. In the case of the **anodes**, the **cheapest is graphite** and the **most expensive are LTO and Silicon combined with graphite.**

For a **battery with the best long-term cost option**, the most successful combination would be **LFP as the cathode and graphite as the anode**. This option provides electric vehicles with a long service life, low cost and high safety. For a **high-performance battery**, **the best option would be NMC+graphite**. This combination is currently the most widely used due to the balance between useful life, power, cost and autonomy. [32]

Below, in Table 18, some of the benefits that determine costs are shown.

Cathode	Anode	Nominal voltage (V)	Energy density (Wh/L)	Specific energy (Wh/kg)	Capacity (Ah)	Life Cycle	Example of electric vehicle
LFP	Graphite	3.2-3,3	-	90-130	-	1000-2000	Chevrolet Spark BAIC EC220
NMC	Graphite	3.65-4,0	200-500	130-241	20-60	1000-2000	VW ID.3 Pro S (2020)
NMC	LTO	2.3	200	89	20	3000-7000	Honda Fit EV (2013)

NCA	Graphite	3.6-3.65	673	200-310	3,2	500	Tesla S (2012)
NCA	Si or SiO-C	3.6-3.65	673	200-310	3,4	500	Tesla X (2015)
NCA	Si+Graphite	3,6-3.65	683	200-310	4,75	500	Tesla Y (2020)

Table 18. Performance of different batteries for electric vehicles [32]

6.5. EVOLUTION OF LITHIUM BATTERIES DEPENDING ON DIFFERENT SCENARIOS

The evolution of the lithium-ion batteries market is directly related to the different political scenarios of the **International Energy Agency** that determine the evolution of the global energy system (Table 19). The electric mobility sector is essential to reduce emissions and decarbonize transport. For an advance towards the evolution of transport electrification, lithium batteries are essential in the transition to a clean energy system. Policies are also a key factor in boosting electric mobility and the demand for these batteries. The ultimate goal is to ensure sustainable supply without overexploiting resources by promoting the recycling of batteries after using them in electric vehicles.

The announced policy scenario (**STEPS**) demonstrates the policies established by different governments today. This scenario indicates that **the consumption of lithium-ion batteries is growing, but it is not enough for the objectives to be achieved**. The existing policy scenario (**APS**) shows the climate policies announced but not implemented. The APS scenario shows **a slow growth of lithium batteries and a domination of fossil fuels**. Finally, the zero-emission scenario (**NZE**) **reflects a massive growth of lithium batteries**. This scenario indicates an evolution without emissions and limits global warming. [33]

Scenario	Impact	Situation for electric vehicles
STEPS	Lithium production does not grow as expected. Low investments in new battery technologies (delay in price drops)	Combustion vehicles are dominated by the lack of powerful policies to switch to electric vehicles. Lithium battery demand grows slowly. Decarbonization of slow vehicles to avoid global warming.
APS	Increased investment in lithium mining, but supply must be even greater. Lithium prices rise (remain high).	Electric vehicles increase in the market, although the transition is slow. The demand for lithium batteries grows (difficulty extraction of Li, Co, etc.). Dependence on fossil fuels in aviation and freight transport.
NZE	Sustainable production and various alternatives.	Electric vehicles become the norm. The demand for electric vehicles is growing. Recycling of lithium batteries is increased. New technologies to have better security, efficiency and durability.

Table 19. Different scenarios for electric vehicles with lithium batteries. [33]

6.5.1 Lithium-ion battery recycle

Recycling is essential to be able to move towards a sustainable world. Taking advantage of the materials after their first use means that there are less overexploitations of primary resources and thus make them last longer. Recycling through a **circular economy** (Figure 13) is an option highly considered by this evolution. **First the raw material is extracted to manufacture the batteries that are used in electric vehicles** in their main use. When the battery capacity is not suitable for the application of mobility, it is used in a **second life** for other utilities, such as energy storage, urban mobility and home use. **At the end of the battery life, when it is** no longer considered functional, its **recycling** is carried out by recovering the materials that can be incorporated into the cycle to be able to create batteries for electric vehicles. Only if it is impossible to recover the materials the batteries are deposited in a permanent elimination. [34]

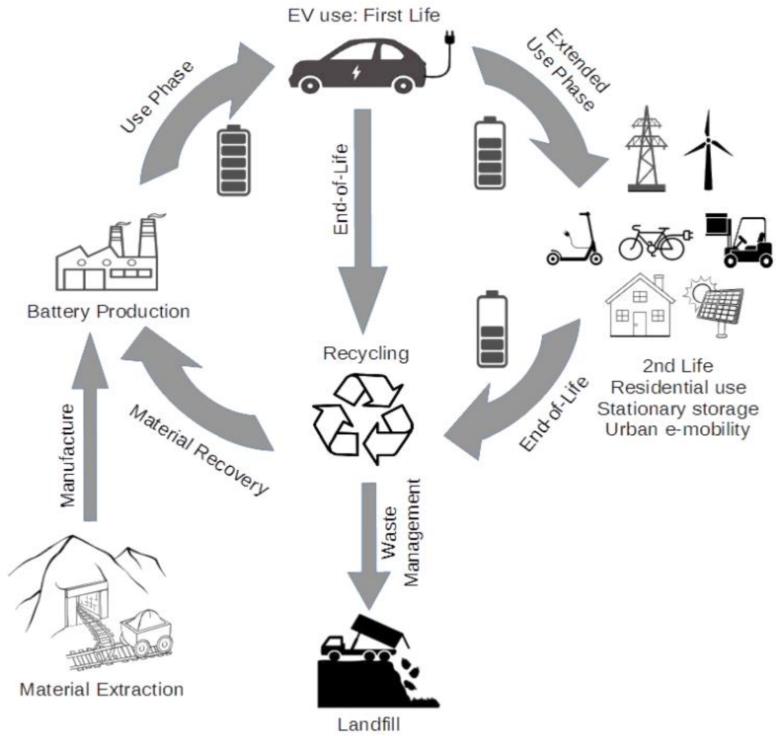

Figure 13: Battery life in a circular economy. [34]

6.6. POSSIBLE ALTERNATIVES TO CURRENT TECHNOLOGY

Currently, lithium-ion batteries are popular in electric vehicles for good efficiency, high energy density and long-life cycle. At present, **the most used cathodes are NMC and LFP and graphite is mostly used as an anode**. To move towards the mass manufacture of electric vehicles, an evolution of technology is required because the current one has some limitations. Figure 14 shows combinations of materials that constitute the batteries represented in a graph that compares the specific capacity with respect to the potential of all of them. It is observed that current battery components are far from the capacity that could be provided by materials that are in the experimental phase. [35]

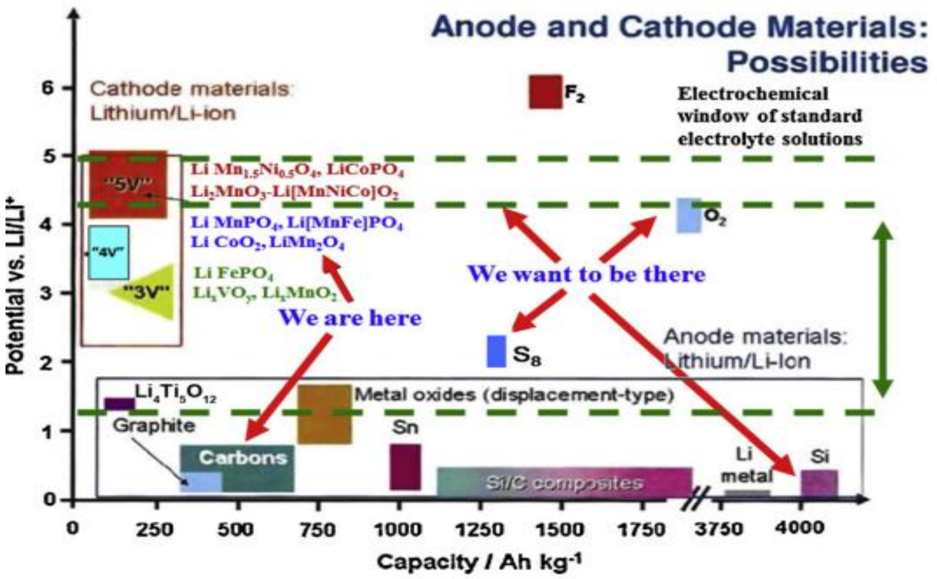

Figure 14: Current and future state of the components of the batteries for electric vehicles. [35]

As advanced anodes, metal lithium and silicon are shown for a higher specific capacity than graphite. On the other hand, as **emerging cathodes**, **O_2** and sulfur (**S_8**) have also a higher specific capacity. With these components the autonomy of electric vehicles grows considerably. However, it is in the experimental phase to advance in problems such as safety, low service life, chemical efficiency and dendrites formation. [35]

Apart from the above options there are alternatives that can be a promising option for an evolution or a substitution. Among the possibilities are sodium-ion batteries, lithium-sulfur batteries, lithium polymer batteries and solid-state batteries (see Table 20).

Alternative Batteries	Advantages	Disadvantages
Sodium ion batteries (Na-ion) [36]	High security Greater abundance Low cost They do not depend on materials that are difficult to access.	Greater ionic size (Na^+ greater than Li^+) Low energy density Volumetric expansion and contraction Low structural stability
Lithium-sulfur batteries (Li-S) [37][38]	High energy density High capacity (1672 mAh/g) Low cost	Formation of dendrites Low conductivity Volumetric expansion and contraction Shuttle effect of polysulfides
Solid state batteries [32]	High safety High energy density Good performance in charging and discharging process.	Low life cycle Low coulombic efficiency Problems in charge interference
Lithium-polymer batteries (Li-Po) [39]	High energy density High security Long useful life	High cost Low ionic conductivity Low stability in charging and discharging process

Table 20. Alternative batteries to lithium-ion.

6.6.1. Alternative battery prototypes

Within the list of batteries of Table 20 there are some prototypes released by some companies. In the case of **sodium-ion batteries**, the Chinese company **Farasis Energy** has presented the **JMEV EV3 vehicle**, which has a range of 251 km, an energy density of 140 to 160 Wh/kg, good safety, adequate performance at low temperatures and a useful life suitable for small vehicles. [40]

Mercedes Benz in collaboration with Factorial Energy is testing a **solid-state battery** prototype that has an energy density of up to 450 Wh/kg and a range of approximately 1000 km. This battery is composed of a solid electrolyte with a metallic lithium anode providing safety by reducing the possibility of fire. [41]

Stellantis, in collaboration with the company **Lyten**, is promoting a plan for Europe and North America called **Dare Forward 2030** that aims to reduce CO_2 emissions and reach a zero-emissions scenario. This plan consists of providing electric vehicles with **lithium-sulfur batteries**, providing high energy density and long range while maintaining the weight of the battery. This plan does not use unsustainable materials such as nickel and cobalt. [42]

Mullen Automotive has developed a prototype of **lithium-polymer battery** in an electric van. This battery offers an energy capacity of 72 kWh and an autonomy of up to 305 km, 73% more autonomy than vans with LFP batteries already available on the market. The prototype with lithium-polymer batteries is expected to be commercially available by the end of 2025. [43][44]

6.6.1. Alternative battery chemistry

6.6.2.1. Lithium-sulfur battery chemistry

In the **discharge process**, elemental sulfur (S_8) is reduced to different lithium polysulfides until Li_2S is obtained (Equation (6)) and the lithium atoms are oxidized releasing Li^+ ions. In the **charge process** (Equation (7)), the reverse process occurs. Li_2S is oxidized until S_8 is obtained and the Li^+ ions return to the anode. [45]

$$S_8 + 16Li^+ + 16e^- \rightarrow 8Li_2S \quad (6)$$

$$8Li_2S \rightarrow S_8 + 16Li^+ + 16e^- \quad (7)$$

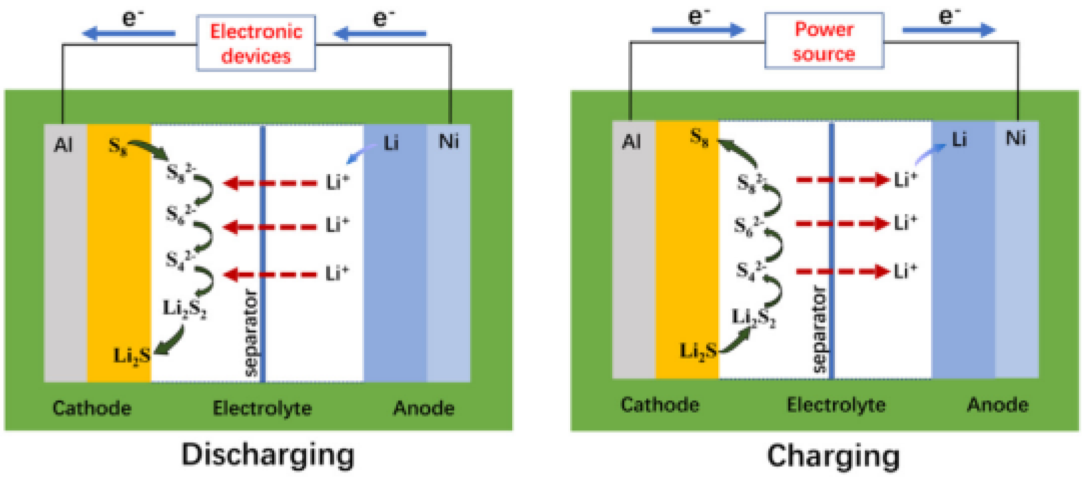

Figure 15: Charging and discharging mechanism of lithium-sulfur batteries.[45] Note in the figure on the right that the term cathode is maintained for the electrode which is the positive pole (the cathode of the cell) when delivering the electric energy (figure on the left), although it is truly the anode in the charging process.

Lithium-sulfur batteries have some limitations. The challenges correspond to insulation properties (polarization and low-rate performance), shuttle effect (low capacity, unwanted polysulfur diffusion and short life) and lithium dendrites (safety problems). [45]

The use of redox mediators is a strategy to overcome the conductivity problem, mitigate the shuttle effect and stabilize the reaction intermediates. During the discharge process the oxidized form of the mediator (RM^{ox}) accepts an electron and it is reduced to RM^{re} (Equation (8)). The electron is transferred to the polysulfide Li_2S_n (long polisulfide) and subsequently reduced to Li_2S_m (short polisulfide) (Equation (9)). The process is reversed in the charging process (Equations (9) and (10)), as represented in Figure 15. [46]

$$RM^{ox} + e^- \rightarrow RM^{re} \quad (8)$$

$$RM^{re} + Li_2S_n \rightarrow RM^{ox} + Li_2S_m \; (m < n) \quad (9)$$

$$RM^{re} \rightarrow RM^{ox} + e^- \quad (10)$$

$$RM^{ox} + Li_2S_m \rightarrow RM^{re} + Li_2S_n \; (m < n) \quad (11)$$

6.6.2.2. Sodium-ion battery chemistry

In Na-ion batteries, Na^+ ions are reversibly transported between the cathode and anode through the electrolyte. There is also electron transport through an external circuit to store and release energy when required (Figure 16). [47]

In the **discharge process**, Na^+ ions migrate from the anode (negative pole) to the cathode (positive pole) through the electrolyte and electrons flow through the external circuit generating electric energy. In the case of the **carbon anode the** reaction given by Equation (12) occurs, whereas it is that of Equation (13) in the case of the **metal oxide type cathode**. [47]

$$Na_yC \rightarrow yNa^+ + ye^- + C \quad (12)$$

$$Na_{x-y}MO_2 + yNa^+ + ye^- \rightarrow Na_xMO_2 \quad (13)$$

The symbol "x" represents the initial amount of Na^+, "MO_2" the cathode material, "C" the carbonaceous material, "y" the electrons that are released, and "Na_yC" the carbon structure with intercalated Na^+.

During the **charging process**, Na^+ ions are extracted from the positive electrode. The reactions are just the opposite to those represented in Equations (12) and (13), which are those given by Equation (14) and (15). [47]

$$Na_xMO_2 \rightarrow Na_{x-y}MO_2 + yNa^+ + y\,e^- \quad (14)$$

$$yNa^+ + ye^- + C \rightarrow Na_yC \quad (15)$$

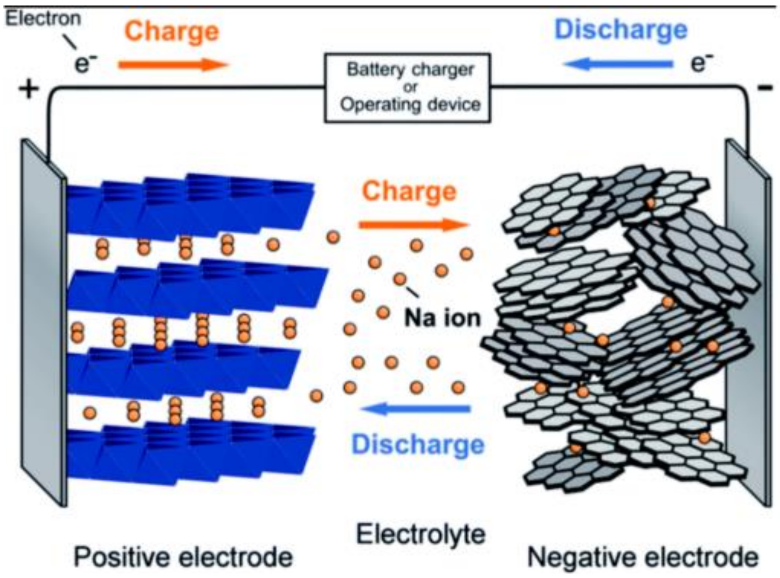

Figure 16: Representation of sodium-ion battery process. [47] Note here that the electrodes have been better designated as positive (cathode under discharge, anode when charging) and negative (anode under discharge, cathode when charging).

6.6.2.3. Solid-state battery chemistry

Solid-state batteries use solid electrolytes to provide high energy density and increased safety. The operation of this type of battery is based on redox reactions typical of lithium-ion batteries. The only difference is that the transfer of Li^+ ions is through a solid electrolyte. In the **discharging process**, metallic lithium is oxidized (Equation (16)) and transferred to the cathode to be intercalated into its material (Equation (17)) obtaining the overall reaction given by Equation (18). In the **charging process**, Li^+ is extracted from the negative electrode and deposited on the positive electrode as metallic lithium (Equations (19) and (20)), Equation (21) being the overall reaction. The symbol "x" corresponds to the mole fraction of lithium ions and "1-x" is the fraction intercalated in the cathode. [48]

$$xLi\ (s) \rightarrow xLi^+ + xe^- \quad (16)$$

$$Li_{1-x}MO_2 + xMO_2 + xLi^+ + xe^- \rightarrow LiMO_2 \quad (17)$$

$$Li_{1-x}MO_2 + xLi\ (s) \rightarrow LiMO_2 \quad (18)$$

$$LiMO_2 \rightarrow Li_{1-x}MO_2 + xMO_2 + xLi^+ + xe^- \quad (19)$$

$$xLi^+ + xe^- \rightarrow xLi\ (s) \quad (20)$$

$$LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi\ (s) \quad (21)$$

Solid-state electrolytes conduct lithium ions between the electrodes and physically separate the anode and cathode. This type of electrolyte prevents the formation of dendrites. Some examples of the most used solid electrolytes are **LGPS** ($Li_{10}GeP_2S_{12}$) and inorganic solid electrolytes such as **LLZO** and **LIC** (Li_3InCl_6). [48]

6.6.2.4. Chemistry of lithium-polymer batteries

Lithium-polymer batteries use a **polymer electrolyte or a gel-like polymer electrolyte**, which makes the battery more flexible, lightweight, and acts as a structural support. The most used polymer electrolytes are **PVDF-HFP** (a copolymer of polyvinylidene fluoride and hexafluoropropylene), **PEO** (polyethylene oxide), and some **conjugated systems** to improve conductivity and safety. Li-Po batteries allow good ion conductivity over a wide temperature range. The development of polymer materials for electrolytes improves problems such as the formation of dendrites due to lithium deposition. [49]

The reactions that take place in Li-Po batteries are those of intercalation and deintercalation of Li^+ ions. In the **discharge process**, energy is supplied, Li^+ ions are released from the anode and intercalate in the graphite layers of the cathode (Equations (22) and (23), respectively). In the **charging process**, energy is stored. In this case, the reactions are reversed to those of the discharge process. Li^+ ions are released from the positive electrode (the cathode under discharge) and reintercalate in the negative electrode (the anode under discharge), as represented in Equations (24) and (25). [49]

$$LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi^+ + xe^- \quad (22)$$

$$xLi^+ + xe^- + C_6 \rightarrow Li_xC_6 \quad (23)$$

$$Li_xC_6 \rightarrow xLi^+ + xe^- + C_6 \quad (24)$$

$$Li_{1-x}MO_2 + xLi^+ + xe^- \rightarrow LiMO_2 \quad (25)$$

Figure 17 shows the scheme of a Li-Po battery. In lithium-polymer batteries, interfacial layers are formed on the electrodes, a layer for the anode called **SEI** (Solid Electrolyte Interphase) and a layer for the cathode called **CEI** (Cathode Electrolyte Interphase). The function of the SEI is to protect the anode without blocking the passage of ions. On the other hand, the CEI prevents surface degradation and secondary reactions of the cathode material. [49]

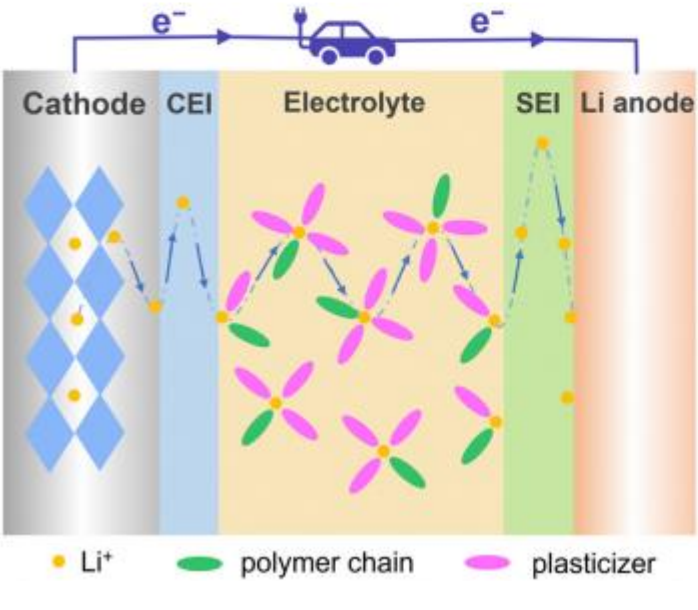

Figure 17: Representation of the charging process for lithium-polymer batteries [49]

7. CONCLUSIONS

The characteristics of lithium-ion batteries make them a dominant option in the mobility sector. The fact that it has **a high energy density, a long useful life and a good efficiency** in the charge and discharge process makes it increasingly opt for its manufacture. The electrochemical operation of the batteries is based on a **reversible movement of lithium ions between the cathode and anode electrodes** during the charging and discharging processes. Among the various types of lithium-ion batteries the most used are NMCs and LFPs. **NMC** batteries have a **high energy density although their materials are more expensive**. **LFP** batteries **have high safety and a long service life**. There are also **Li-Po** batteries that are used less. These batteries stand out for their **low weight and their flexibility in shape and size** making them suitable in light electric vehicles.

The cost of lithium batteries has decreased in recent years due to the increase in their production and the improvement in manufacturing technologies. This has led to the incorporation of lithium-ion batteries into electric mobility. Some raw materials such as nickel and cobalt are expensive and scarcer than other materials, this makes the price drop lower. **One of the long-term alternatives that can offer a lower cost would be Li-S batteries**, since sulphur is cheaper and more abundant although its technology still needs to be improved due to its low service life and the degradation of the electrode.

Currently, Li-ion batteries are the best option for electric vehicles, but it **is essential to consider alternatives and focus the future on developing technologies** that provide solutions to environmental problems and the lack of materials. Among the **most common alternatives are sodium batteries and solid-state batteries**. Na-ion batteries have more abundant and easily accessible materials, the disadvantage they have is low energy density. Solid-state batteries have high energy capacity and high safety.

To intensify lithium-ion batteries in vehicles on the market, it is important that there are **policies that promote an energy sustainable model**. The international energy agency presents the scenarios to continue in **the electrification of vehicles** and move towards sustainability. A political strategy of governments with more international power that encourages the **use of renewable energies and a circular energy economy thanks to the recycling and reuse of batteries** is essential to continue in the development of technologies that offer more electric vehicles to go to the market.

Electrifying electric vehicles builds **decarbonization and reduces dependence on fossil fuels**. With this decision, it improves air quality and moves towards the use of renewable energies. To achieve the objectives for a complete transition from fossil fuels to electric vehicles, it is recommended **to improve the charging infrastructure, encourage commercialization, encourage recycling and continue research** to improve the type of existing batteries.

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9. ACRONYMS

APS: Announced Pledges Scenario

ATM: Automated Teller Machine

BEV: Battery Electric Vehicles

BMS: Battery Management System

CEI: Cathode Electrolyte Interphase

EC: Ethylene Carbonate

GPE: Gel Polymer Electrolyte

IL: Ionic Liquid Electrolytes

LCO: Lithium Cobalt Oxide

LFP: Lithium iron phosphate

LGPS: Lithium Germanium Phosphorus Sulfide

LIC: Lithium Indium Chloride

Li-ion: Lithium-ion

Li-Po: Lithium-polymer

Li-S: Lithium-sulfur

LiTFSI: Lithium Bis(trifluoromethanesulfonyl)imide

LLZO: Lithium Lanthanum Zirconate

LMO: Lithium Manganese Oxide

Na-ion: Sodium-ion

NCA: Nickel Cobalt Aluminum

NMC: Nickel-manganese-cobalt

NZE: Net Zero Emissions

PAN: Polyacrylonitrile

PBI: Polybenzimidazole

PEI: Polyetherimide

PEO: Polyethylene Oxide

PEO-LiTFSI: Polyethylene Oxide-Lithium Bis (trifluoromethanesulfonyl) imide

PET: Polyethylene Terephthalate

PHVEV: Plug-in Hybrid Electric Vehicle

PP/PE/PP: Polypropylene/Polyethylene/Polypropylene

PVDF: Polyvinylidene Fluoride

PVDF-HFP: Polyvinylidene Fluoride-Hexafluoropropylene

PVDF/PEO: Polyvinylidene Fluoride/Polyethylene Oxide

PVA-$LiClO_4$: Polyvinyl Alcohol-Lithium Perchlorate

PYR14TFSI: 1-Butyl-1-methylpyrrolidinium Bis (trifluoromethanesulfonyl) imide

SE: Solid Electrolytes

SEI: Solid Electrolyte Interphase

SOC: State of Charge

SOF: State of Function

SOH: State of Health

SPE: Solid Polymer Electrolyte

STEPS: Stated Policies Scenario