THESIS

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A CRITICAL REVIEW OF THE ENVIRONMENTAL IMPACT OF SOLID-STATE BATTERIES IN CONTRAST TO NMC, NCA AND LFP LI-ION BATTERIES

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Abbreviations:

SSB: Solid-State Battery

NCA: Nickel Cobalt Aluminum

NMC: Nickel Manganese Cobalt

LFP: Lithium Iron (Fe) Phosphate

mAh: milliampere hour, 1 mAh means the battery can maintain a current of 1 milliamp for 1 hour

kWh: non-S.I. unit of energy equivalent to 3.6 megajoules

gWh: gigawatt-hour

g: gram

C: C rate or the speed with which a battery can be charged/discharged

LLZO: Lithium Lanthanum Zirconium Oxide

LLZTO: Lithium Lanthanum Zirconium Tantalum

V: Volt, S.I. unit for potential difference

m: mass

v: velocity

CO_2 – equivalent: Carbon dioxide equivalent

u: atomic mass unit

cm: centimeter

GWP: Global Warming Potential

ppm: parts per million

1. Introduction

In physics, energy is most often defined as the ability of a body to perform work. (Agnoletti & Neri Serneri, 2014) We could define energy in economic terms as the capacity of performing work, useful for human beings, thanks to changes introduced with some cost or effort in the structure of the matter or its location in space. (Agnoletti & Neri Serneri, 2014) All life on Earth depends on the energy emitted by the sun, which essentially comes from the nuclear fusion of hydrogen into helium. (Fowler, 1984) When mankind started understanding the physical laws this world obeys, especially thermodynamics, they were able to invent the steam engine, to convert heat from burning coal into usable mechanical energy.

There were other forces and kinds of energies that existed which were not understood, for example, many philosophers and thinkers thought magnetism was a celestial force or one produced only in mountains in certain regions. (Gilbert et al., 2022) However, magnets remained mysterious long after they were characterized, and their properties established. That is until Ørsted observed that when a magnetic needle is brought into the field surrounding a current carrying wire, it will set itself tangent to the circular field. (Shanahan, 1989) This was the first electromagnet, and it gave us the ability to generate electricity.

This ability also meant that electricity was to become a commodity in households and due to this, by the end of the 20th century, energy consumption per person, on a world scale, was about 58 kWh per day. (Agnoletti & Neri Serneri, 2014) Recently, the focus has shifted towards using more renewable energy sources and moving away from traditional sources such as coal (which was used in the earliest engines and power plants), this change is due to growing environmental concerns and the volatility of oil prices. (Mukhtarov, 2024)

Storing electrical energy in the form of chemical energy so it is readily available to be used at any time is of significant importance, regarding stationary uses or for electric vehicles. The ongoing development of lithium-ion batteries with respect to the challenge high energy density in combination with high safety, will give another push to the success of the electric vehicles, subsequently, leading to an overall carbon dioxide reduction. (Gutmann, 2013)

Currently, NMC, LFP and NCA li-ion batteries share the top spots in electric vehicle batteries. (Jones, Elliott and Nguyen-Tien, 2020) However, due to safety issues, limited energy densities and others, researchers are focusing on Solid-State Batteries (SSB) since they are set to overcome the safety issues inherent to liquid electrolyte batteries such as fire and leakages and they have higher energy densities also due to the reduction in volume from liquid electrolytes to solid electrolytes. (Yuan and Yuan, 2024)

The purpose of this study is to attempt to provide an overview of the potential environmental impact of SSBs in contrast to the existing batteries. Despite some challenges faced when attempting to give a full review of all the risks that SSBs pose to the environment and whether they are a safe alternative to what is already on the market, it is vital to highlight any potential environmental perils before it can grow out of proportion. Therefore, the goal of this research is to attempt to establish what is to be expected, in terms of the environmental repercussions, following the commercialization of SSBs.

Personally, I have always closely watched the developments connected to clean energy and the potential for growth in some of the more premature ideas. Clean and renewable energy are inseparable from battery technology as they are a vital part of optimizing renewable energy facilities. I was also interested in electrochemistry as a subject, owing partly to the fact that during my high school studies, I designed and 3d-printed a small drone, which was later destroyed by the battery overheating during charging. This incident later led to me studying the chemical properties of the batteries I wished to purchase to ensure future success in my high school graduation project. Solid-State batteries being one of the safest options for future applications certainly piqued my interest to begin my research and assess whether they are also a viable option in terms of environmental friendliness.

2. Literature Review

2.1 Energy

2.1.1 Defining Energy

In physics, energy is most often defined as the ability of a body to perform work. (Agnoletti & Neri Serneri, 2014) This definition, however, simplifies our current understanding of energy, its usages and the economical role it plays in today's industrial and technological world. Therefore, I see we must delve into the origin of the word itself if we are to understand it in the right context.

The word energy originated with the renowned philosopher Aristotle (384–322 BC). His *ἐνέργεια* (energeia) laid the foundations for the Latin adaptation of the word; *energia*, the French; *énergie* (first used in the sixteenth century), and the English energy (originating also around the sixteenth century). (Cara New Daggett 2019)

The topic of energy is later expanded as Descartes and Leibniz both in their own ways attempted understanding the concept. Descartes argued the conservation of momentum (mv) while Gottfried Leibniz argued the conservation of kinetic energy (mv^2). (Cara New Daggett, 2019) Both were eventually proved correctly without their findings being mutually exclusive. However, Leibniz's most relevant belief regarding the definition of energy is perhaps his belief that bodies must not be only matter (passive) as Descartes argues, rather their existence is best captured in their activity, motion and change across time. (McDonough, 2024)

2.1.2 Origin of Energy

Despite the industrialization and extensiveness of our use for energy, in order to encapsulate the idea, we must understand the origin of energy. All life on Earth depends on the energy emitted by the sun, which essentially comes from the nuclear fusion of hydrogen into helium deep in the solar interior. (Fowler, 1984). Man has from the very earliest ages looked up with a feeling of awe and wonderment to our great luminary, to whom we owe not only the light of day, but the genial warmth by which we live. (Siemens, 1882) The giant star in the sky also provides the energy needed by vegetation to produce the food with which animal life is maintained and henceforth, is indispensable for humans.

During the Mesolithic era, the rise in temperature enabled humans to increase cultivation and particularly cereals, a later development in the agricultural transition came from about 5,000 years ago, in 3,000 BCE when humans were able to tame more animals and further utilize them in agriculture and transportation, this also led to several other innovations which increased the efficiency of agricultural practices. (Agnoletti & Neri Serneri, 2014) This represents the evolution that allowed for human beings to have an easier access to a steady supply of food which would later allow for a rise in knowledge and consequently, the technology that we enjoy nowadays.

However, a more relevant revelation regarding energy is the utilization of heat energy to benefit mankind. In a paper published in 1874, Professor Robert H. Thurston summarized Professor Tait's "Sketch of Thermodynamics" and his 9 points towards mankind's understanding of thermodynamics as it stood at the time. Rewording the theories written by Professor Robert could possibly alter the meaning of the statements as they are mostly theories set forth by scientists, therefore, I have decided to include the excerpt from the paper in the paragraph below.

1. Newton's grand general statement of the laws of transference of mechanical energy from one body or system to another (1687).
2. Davy's proof that heat is a form of energy subject to these laws (I799).
3. Rumford's close approximation to a measure of the mechanical equivalent (1798).
4. Fourier's great work on one form of dissipation of energy (1812).
5. Carnot's fundamental principles, his cycles of operation, and his tests of a perfect engine (1824).
6. Thompson's introduction of an absolute thermodynamic scale of thermometry (1848).
7. Joule's exact determination of the mechanical equivalent of heat, and the general reception of the true theory in consequence of his experiments (1843-9).
8. The adaptation, by Clausius and Rankine, and subsequently, with greater generality and freedom from hypothesis, by Thompson, of mathematical investigation (partly based on Carnot's methods) to the true theory; the reestablishment of the great second law by Clausius, with Joule's experimental verification of Thompson's general results (1849-51).
9. Thompson's theory of dissipation (1852).

(Thurston, 1874)

2.1.3 Economic Development of Energy

I have, so far, attempted to mention the development of our understanding of energy and the emergence of theories regarding thermodynamics to introduce the fundamental foundations which eventually led to the development of the steam engine which, after its commercialization, changed the world to the one we know today. The first mention of steam engines can be traced back to Hero of Alexandria in Egypt around 150BC, but the first workable coal powered steam pump was made by Thomas Savery in 1698, however, it was improved upon by Thomas Newcomen in 1712, and Newcomen's engine could reliably raise water over 50 meters making it extremely beneficial for the mining industry. (Spear, 2008) Figure 1 below shows a diagram of a Newcomen steam engine.

The water is boiled in the boiler as can be seen in the diagram, when the steam enters the cylinder, it pushes the piston upward, moving the beam on the left downward. The valve allowing steam to travel from the boiler is closed and the valve admitting water is opened to cool down the steam in the cylinder. When the steam condenses, this creates a vacuum which pushes the piston downwards and the beam subsequently upwards. The beam usually converts the linear motion to a rotary or oscillatory motion.

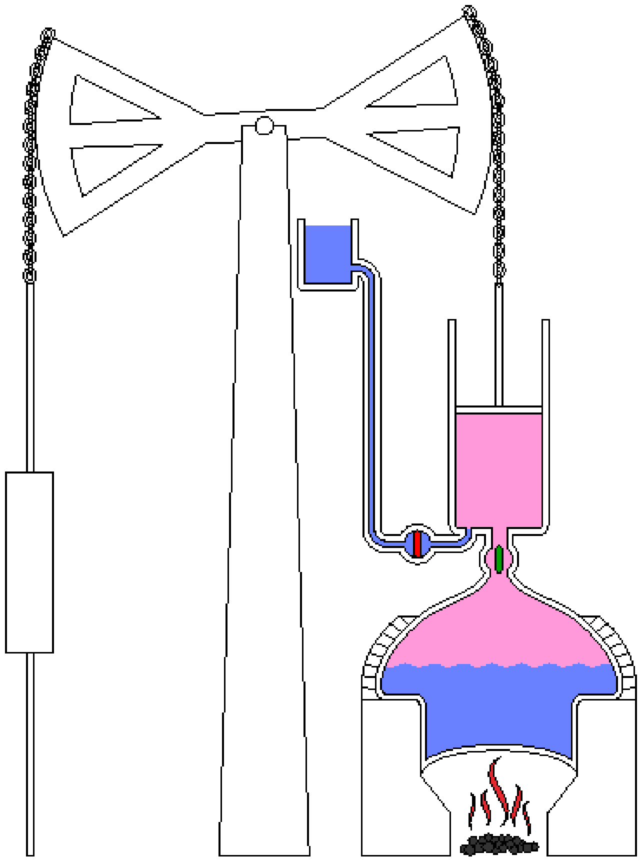

Figure 1 Diagram of a Newcomen engine (Emoscopes, 2023)

Defining energy as it is conventionally defined in a physics context is an important step towards further understanding energy which is why it was the first sentence in this article. However, with the utilization of steam engines in mining practices and their eventual incorporation into other industries also means a new definition is warranted for energy in a commercial or economic context. We could define energy in economic terms as the capacity of performing work, useful for human beings, thanks to changes introduced with some cost or effort in the structure of the matter or its location in space. (Agnoletti & Neri Serneri, 2014)

With the view that energy can be harnessed for economic profitability, it became apparent that Newcomen's engine was not satisfactorily efficient. Wider applications for steam engines became possible when James Watt, in partnership with Matthew Boulton were able to separate the condensation process of steam from the main cylinder to another cylinder, this avoids the need for the main cylinder to undergo alternate heating and cooling, this reduced coal consumption and subsequently made it possible for the Boulton-Watt atmospheric steam engines to be used as stationary power plants. (Wang, 2022)

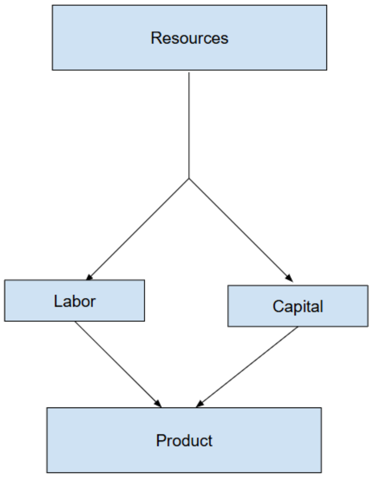

Figure 2 Basic structure describing the economical perspective of viewing energy (my own work inspired by Agnoletti & Neri Serneri, 2014

Figure 2 above describes how mechanical energy came to play a role in the economy. Considering the engine and fuel cost the resources needed and energy as the product, energy production and its varied applications were viewed as one of the most efficient ways to increase profit as it made a lot of processes (such as mining) cheaper and easier.

2.2 Electrical Energy

2.2.1 Early Development of Electricity

While this field of mechanical energy and power astonished the public due to its capabilities, in the 17th century, William Gilbert (1544-1603) published his book *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* which contained his research about electricity and magnetism using new terms such as “electric attraction”, “electric force” and “magnetic pole” making him the first scientist to use them. (Erdinc & Tescikaraoglu, 2019)

William Gilbert - or Gilberd, as he wrote it - was born in 1540 at Colchester, County Essex, England, of which borough his father, Jerome (Hieron) Gilberd, was recorder. (Gilbert et al., 2022) In May 1558, he entered St. John's College, Cambridge (although some say he attended Oxford), proceeding B.A. 1560, Fellow 1560-1561, M.A. 1564, mathematical examiner 1565-1566, M.D. 1569. (Gilbert et al., 2022)

When undertaking a topic such as the early history of electricity, it becomes rapidly transparent that its discovery is owed mostly to magnetism as a phenomenon. William Gilbert first starts his book by mentioning the many fairytales and fables that have been constructed about magnetic forces, enigmatic as they were at the time. He mentions many philosophers and thinkers who thought magnetism was a celestial force or one produced only in mountains in certain regions. Gilbert then goes on to use experimental methods to determine that each loadstone (the earliest magnetic mineral discovered) possesses two poles regardless of its outwardly shape or texture. (Gilbert et al., 2022) One of the experiments conducted and shown clearly in the book is demonstrated in Figure 3 below.

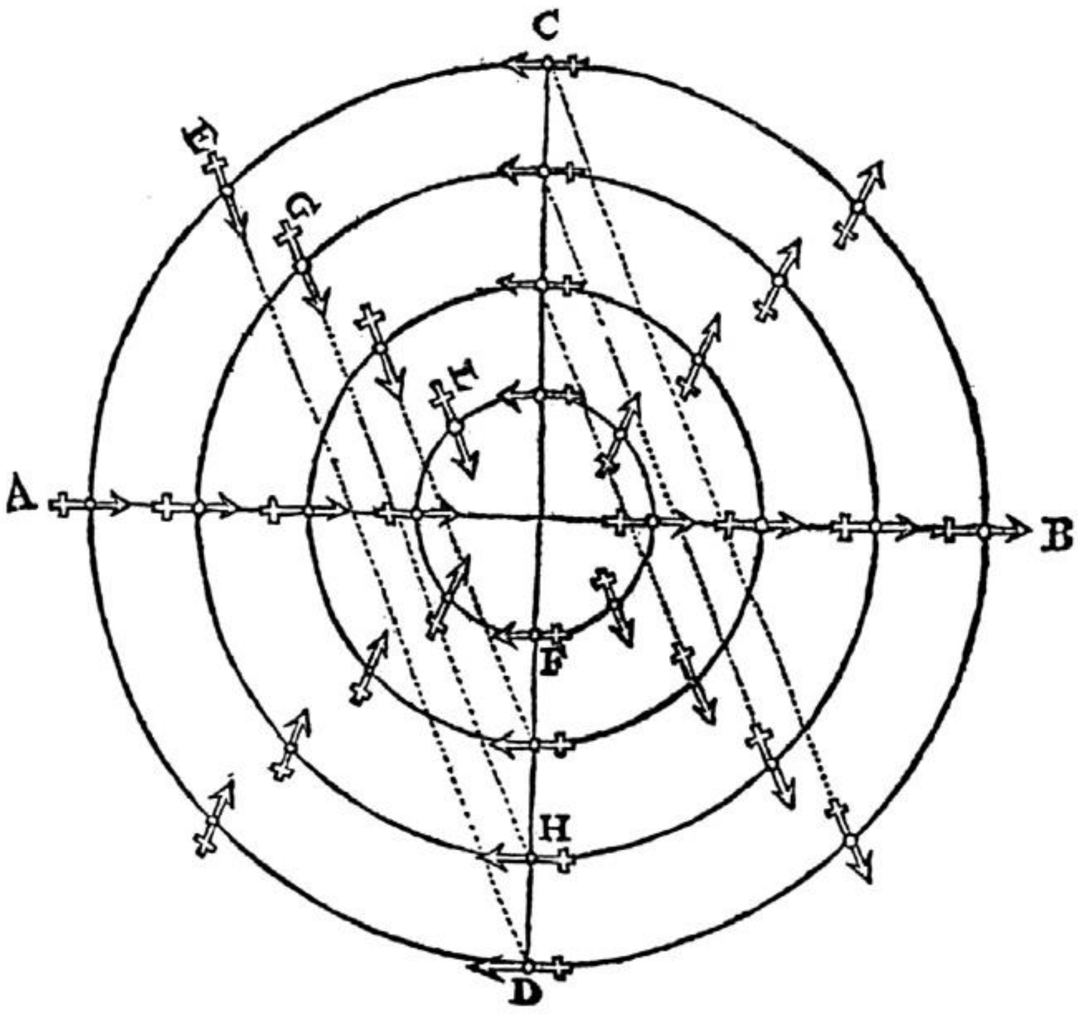

Figure 3 Magnetic bodies interacting with a magnetic orb (Gilbert, De magnete)

In this diagram, a magnet (loadstone), shaped into a fine orb, is placed stationary while a smaller magnetic body of known poles is placed in different locations throughout the loadstone. The alignment and angle at which the magnetic body sits still can be used to determine many of the loadstone's magnetic properties. (Georgescu, 2014)

Following William Gilbert's work were two of his students, Otto von Guericke (1602-1686) and Robert Boyle (1627-1691). (Erdinc & Tascikaraoglu, 2019) Before discussing Guericke's contributions to the field of electric energy, it is worth noting that he conducted several research experiments regarding atmospheric pressure, sound media, among others which inspired many scientists in the following decades to use his work to extend our understanding of physics and chemistry. (Coulson, 1943) Guericke experimented with static electricity to show how excited bodies attract and repel, he also came up with a discovery, which, despite being easily dismissed as being too vague, when combined with the inspiration it stirred in others such as Francis Hauksbee, its effect becomes much greater, the observation being "If you take a globe with you into a dark room and rub it, especially at night, light will result.".

(Coulson, 1943) In this sentence lies the source of the first electrically induced light which is not the result of nature as in electric eels or lightning.

Francis Hauksbee (1660-1713) is credited with creating the electrostatic generator seen below, it worked by rapidly rotating the glass globe and placing his hand over it to excite the globe. (Home, 1967) Hauksbee then went on to conduct several experiments using this apparatus to reach several conclusions including conductive materials, the existence of opposing charges which attract and like charges which repel. (Home, 1967) However, our understanding of electricity remained unrefined at the time, allowing for later scientists to further this field.

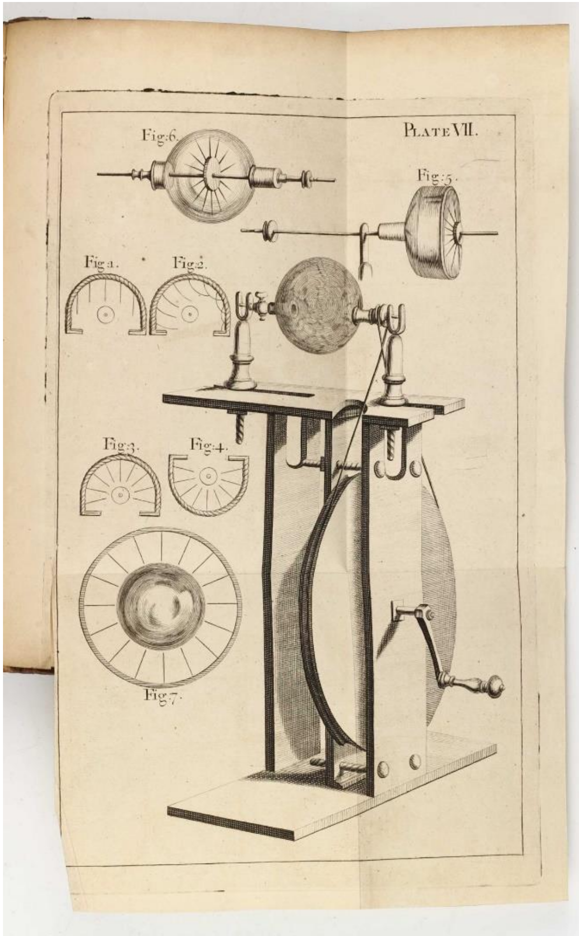

Figure 4 Hauksbee Electrostatic Generator (Hauksbee, 2021)

Stephen Gray (1666-1736) furthered Hauksbee's ideas by using lines of packthread up to several hundred meters long, suspended by silk thread, and holding a rubbed glass rod at one end appropriately. The ball suspended at the other end would exert the usual attraction, this allowed him to conclude that electricity could be transmitted along conducting lines, provided these were supported appropriately. (Home, 2002)

Inspired by those that came before him, and especially Stephen Gray, Charles-Francois de Cisternay du Fay (1698-1739) conducted many experiments which led him to several conclusions, most notably, the existence of two distinct kinds of electricity, resinous (-) and vitreous (+), known today as negative and positive charges, respectively. ("Bicentenary of Du fay (1698–1739)," 1939)

Soon after these discoveries came someone by the name of Pieter van Musschenbroek (1692–1761) who performed the Leyden experiment that would shock the world. The experiment is simple, it is a bottle containing water suspended from the collector of an electrical machine by a metal hook passing through the cork into the water. (Home, 2002) Pieter announced his success at creating what is now called a capacitor through the following announcement 'I thought it was all up with me', this was to signify the intensity of the shock he felt from the Leyden jar. (Home, 2002)

On June 15, 1752, Benjammin Franklin (1706-1790) conducted his most memorable kite experiment, using wet hemp as the kite's string, which could conduct electricity from the lightning in the thunderstorm down to the iron key that hung on the end of the string. (Erdinc & Tascikaraoglu, 2019) Franklin also used dry silk ribbon to prevent the lightning from discharging onto his body. When he witnessed a spark jump from the key to his knuckle, he was able to prove that lightning was certainly electrical in nature. (Erdinc & Tascikaraoglu, 2019) This later led him to discover that lightning rods (which are still in use today) could be placed on the tops of buildings for transferring charges to the ground by using metal wire without any harm. (Erdinc & Tascikaraoglu, 2019)

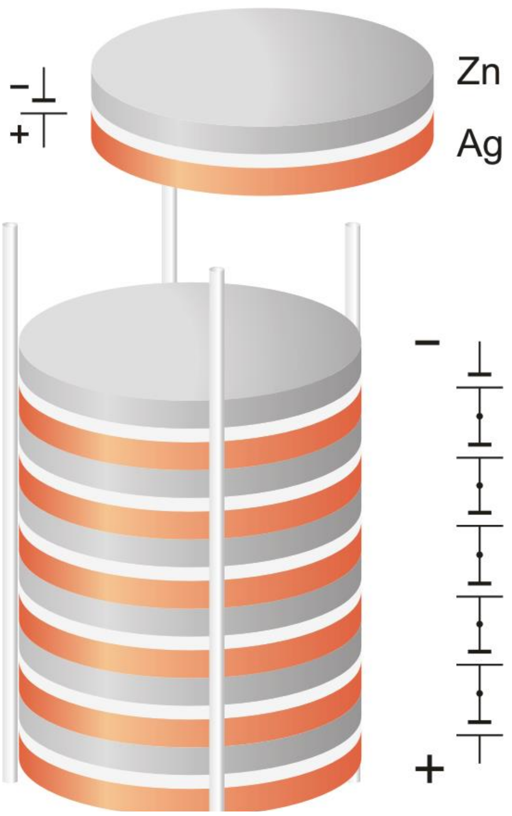

Figure 5 A diagram of the Voltaic pile/electric 'pile' (Generalic et al., n.d.)

Henry Cavendish (1731-1810) conducted experiments to test the resistance of different salt solutions using Leyden jars, according to his manuscripts, his body served as a galvanometer, which means that he gauged a solution's resistance based on the intensity of the shock felt as a result. (Susskind, 1950) His next step was to test how resistance of these solutions varied according to the current passing through them, this could be regarded as the basis for Ohm's law, which only came around 50 years later. (Susskind, 1950)

Later, the controversy which resulted in what is today considered one of the major milestones in electricity was between Luigi Eliseo Galvani (1737-1798) and Alessandro Volta (1745-1827), and the main dispute was over the origin of the electricity involved in the muscle contractions brought about by metallic conductors in frog preparations: Volta the physicist asserting that this electricity was produced by metals, and Galvani the physiologist, claiming that it was intrinsic to the organism. (Piccolino, 2000) With a letter dated 20th March 1800, Alessandro Volta announced to the world his invention of the 'electric pile', the first device capable of continuously providing an electrical current. (Trasatti, 1998)

2.2.2 Modernization of Electricity and Commercialization

As far as the scientific field of electricity was concerned at that point in time, electricity was used mainly in laboratories and for amusement by entertainers. However, with Humphry Davy (1778-1829), and his installment of the largest battery in the world, made up of 800 voltaic batteries, underneath the Royal Institution, this was about to change. (Erdinc & Tascikaraoglu, 2019) When Davy connected the voltaic batteries to two carbon rods, he observed a bright light, setting the base for others, like Thomas Alva Edison to further this field of commercial light. (Erdinc & Tascikaraoglu, 2019) Davy's contribution to electrochemistry were nothing short of astounding as he was the first to isolate calcium, strontium, barium, and magnesium using electrolysis, moreover, he also invented the Davy lamp in 1815 after a coal mine explosion in 1812, his invention, which relied on illumination by fire, significantly reduced the risk of such incidents in the future. (Russell, 1978)

Until this point in time, we have discussed the early literature that explained magnetism and then this was followed by a summary of the most relevant discoveries regarding electricity, however, there was one missing component, namely the connection between electricity and magnetism. Hans Christian Ørsted (1777-1851) in April 1820 observed that when a magnetic needle is brought into the field surrounding a current carrying wire, it will set itself tangent to the circular field. (Shanahan, 1989) André-Marie Ampère (1775-1836) later expanded on Ørsted's finding by winding the wire into a helix which he called a solenoid to obtain a stronger magnetic field. (Herlach, 2002)

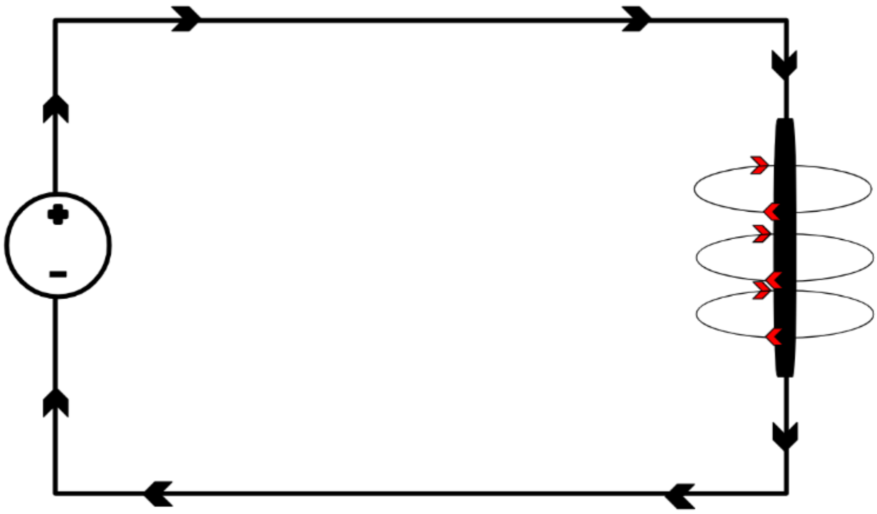

Figure 6 Ørsted's law. The black arrows denote the direction of the current while the red arrows denote the N of the magnetic field (my own work inspired by (Electrical Technology, 2020))

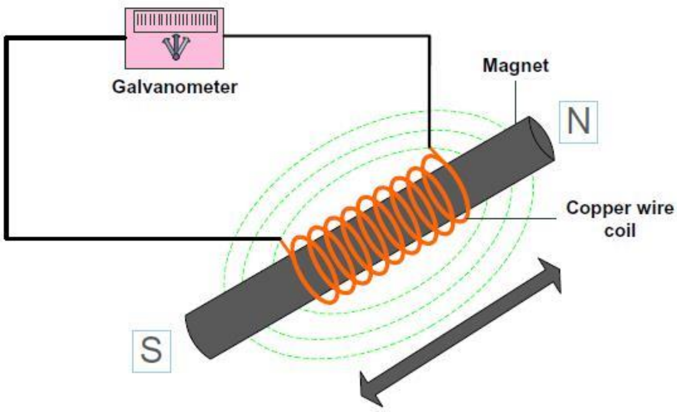

Figure 7 Faraday's electric generator (Erdinc & Tascikaraoglu, 2019)

After the discovery of such an important phenomenon as electromagnets, attention to electricity grew, and this helped Michael Faraday's (1791-1867) numerous contributions to electricity. Michael Faraday believed that since electric current results in a magnetic field, then a magnetic field should also influence the current, which led him to one of his most important discoveries; that a wire placed next to a current-carrying wire will be moved and a current will be produced in that wire, opposite the direction of current in the primary wire. ("The experiments of Faraday, Nobili, and Antinori, on a new class of electro-dynamic phenomena," 1832) Since using a solenoid creates a stronger magnetic field, Faraday went on to experiment further using solenoids, different materials for wires, varying currents and other factors, until he created the most efficient generator he could, which is fairly similar to the ones installed in today's power plants. (Erdinc & Tascikaraoglu, 2019) It is also important to note that these experiments, despite being written and documented thoroughly in Faraday's memoir, they were carried out without involving mathematics. (Helmholtz, 1881)

This discovery was closely followed by Samuel Morse's (1791-1872) invention of the electromagnetic telegraph and was given a chance to present it. In a paper written in 1838, William Hamilton explains the working mechanism of Morse's electric telegraph as follows: A galvanic battery is connected to a circuit of 10-mile-long circuit, in the middle of this circuit stood the register which contained an electromagnet, around which were coils from the circuit, when current is flowing, a fountain pen near the electromagnet will leave a trace on a piece of paper, on the other side, near the battery, the wires were placed in two cups filled with mercury, so that only when a bent wire connects the contents of the cups, can a message be written on the paper on the register's side, the telegraph works by moving this bent wire in and out of the cups to print out dots and dashes. (Hamilton, 1838) These messages were transmitted in Morse code, which was developed primarily for the telegraph. This was an important milestone for electromagnetism and its commercialization.

Finally, the biggest leap assisting the spread of electric power from an unknown phenomenon to a luxury to be enjoyed by most people around the world, even to the extent that it can be argued that it has become a necessity, came from the man named Thomas Alva Edison (1847-1931). Edison became known as the person who created the first commercial, practical, and affordable incandescent lamp for home illumination. (Erdinc & Tascikaraoglu, 2019) However, Edison is also credited for having some of the earliest power plants built, one example is the central Edison station in the first district of New York, which was planned to contain 12 dynamos, each capable of supplying 1400 lights, at 16 candle-power incandescence. (Edison & Porter, 1882) The next stage in the distribution of electricity was to ensure its effectivity and safety, both features which were lacking in Thomas Edison's design, and this resulted in the famous dispute between him and Nikola Tesla (1856-1943). A paper was published in 1896 which highlights the shortcomings of DC (direct current) in terms of electric transmission and how AC (alternating current) can be utilized to lower the current using step-up transformers for increased safety and minimal losses. (Emery, 1896)

2.2.3 Current Demand for Energy

It has been well over a century since the discoveries I mentioned were made, and since then, electricity has gone from being a mere scientific curiosity to becoming a commodity. I found it important to outline

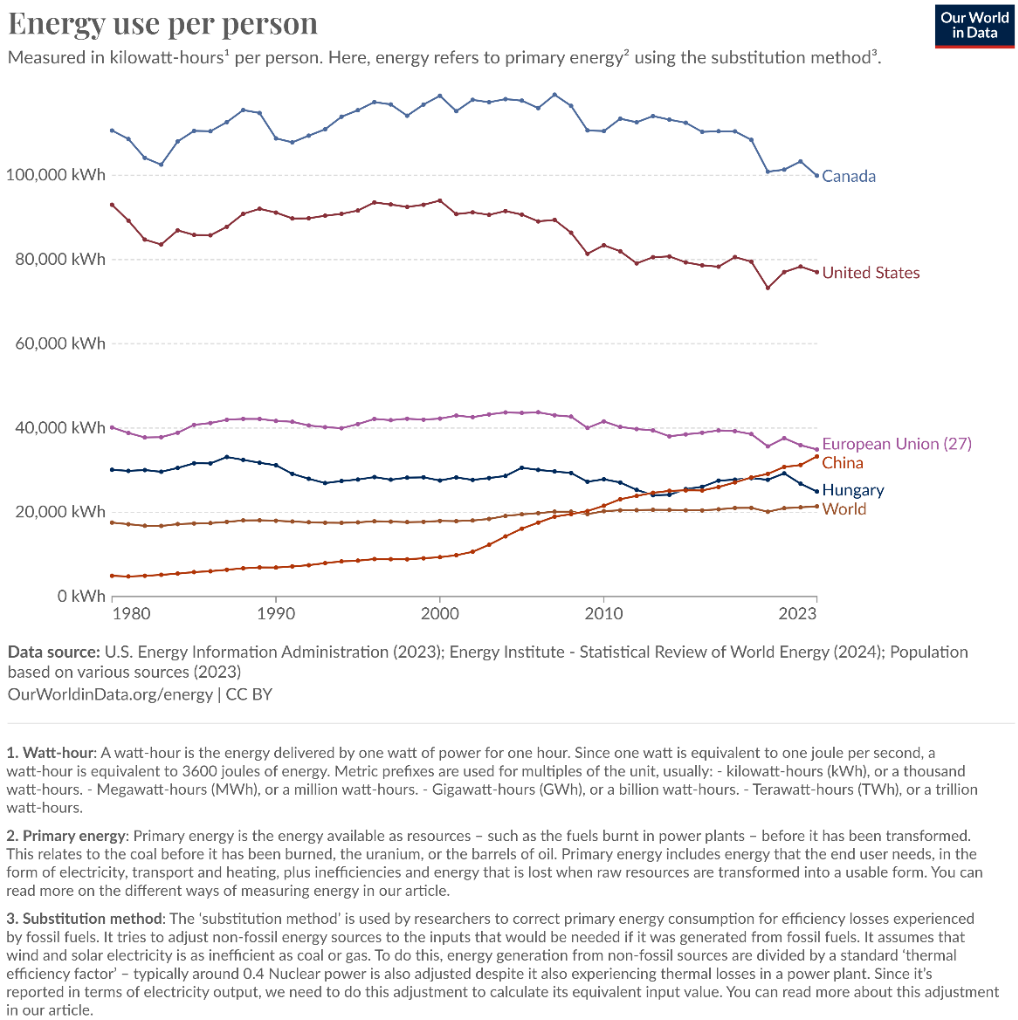

Figure 8 Energy Consumption per capita in the world, highlighting some countries (Ritchie et al., 2020)

the developments which enabled us to reach this state with electricity because the sheer amount of research conducted in those times meant that the same materials, equations and machinery are still applicable today. However, the largest difference between then and now is the scale at which this operation is now working. By the end of the 20th century, energy consumption per person, on a world scale, was about 50,000 kcal per day, or around 58 kWh per day. (Agnoletti & Neri Serneri, 2014)

Figure 8 is a chart showing the growth in energy consumption per capita per annum over the last few decades.

As can be seen by Figure 8, there is a clear difference in consumption among the countries, depending on the countries' sizes and the widespread access to electricity, transportation, heating and others. Recently, the focus has shifted towards using more renewable energy sources and moving away from traditional sources such as coal (which was used in the earliest engines and power plants), this change is due to growing environmental concerns and the volatility of oil prices. (Mukhtarov, 2024)

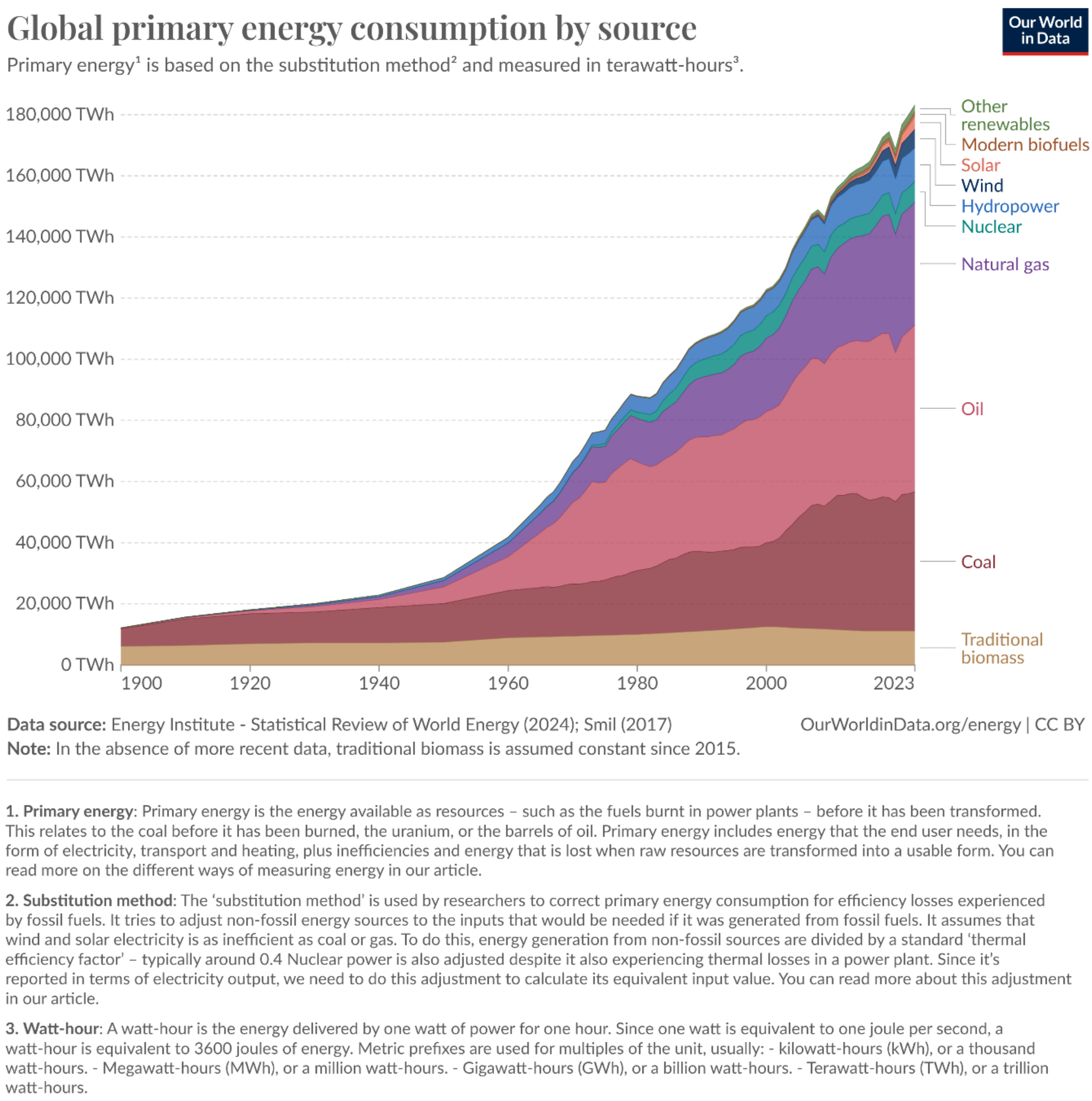

Figure 9 Energy sources around the world (Ritchie et al., 2020)

2.3 Energy Storage

2.3.1 Early Energy Storage

Since the beginning of humans as a species, 5-7 million years ago, and for an estimated 85-90% of human history, food was the only source of energy. (Agnoletti and Neri Serneri, 2014) With the development of agriculture, wind and water mills started taking advantage of the potential energy stored inside currents. (Agnoletti and Neri Serneri, 2014) Organisms all store energy, which is much needed for metabolic reactions, however, our dependence on energy makes use of any energy-storing mechanism so that it can be converted to a usable form. One example of such a thing is sand storage, where instead of using lithium ion batteries to store excess electricity from renewable sources, sand is heated using the electricity to around 500 degrees Celsius and can be used to pump hot air to households, to paint a clearer image of the prospect of “sand batteries”, a one gWh sand battery can provide heat to more than 30 thousand UK homes every day. (Gill, 2022)

Breaching the topic of the earliest form of energy storage is difficult, as coal could be considered the first, since it effectively stores the potential for heat upon combustion. It can also be argued that soil is the earliest form of energy storage, since, along with energy from the sun, it stores the nutrition needed by different plants which gives fruits and vegetables their calorific value, or energy, to be later utilized by animals. However, since this paper is focused on batteries, we will only consider the technologies with which we are able to store chemical energy that can be directly transformed to electric energy, leaving the storage of other forms of energy to avoid redundancy. To define batteries, I will give a summary of their principle: due to chemical reactions in the electrodes, electrons move between the electrodes, creating an electrical potential difference. (Kumar et al., 2024)

2.3.2 Battery Types

The earliest battery dates to around 2,200 years ago, discovered near modern day Baghdad, Iraq, and through experimentation, it was determined that it could generate 1.5 to 2.0 volts, unfortunately, it remains speculation what this battery was used for. (Danila, 2015) The next discovery worth mentioning is the Leyden Jar, however, this is now considered a primitive capacitor. (Perkins, 2017)

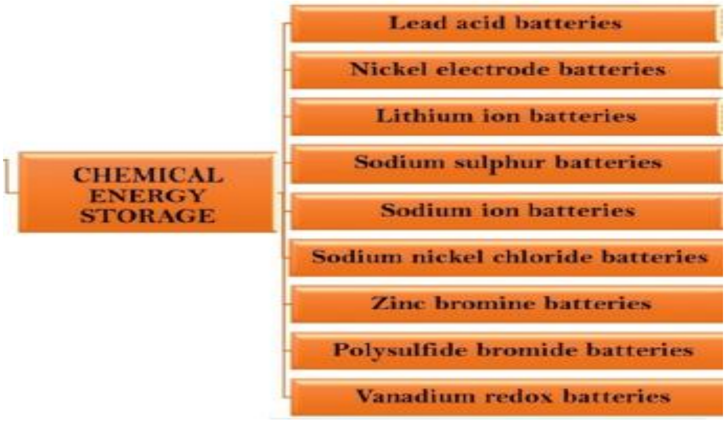

Figure 10 Different types of batteries and their chemical composition (Khan et al., 2024)

Lead acid batteries were developed in large quantities in 1880, when Emile Alphonse Faure invented the "sticky plates", coating lead plates with a paste of lead powder and sulfuric acid which increases the storage capacity of the battery. (Danila, 2015) Lead acid batteries underwent a lot of development and are still widely used since they are cheap to produce and have a high energy discharge rate, however, they have a relatively low amount of energy storage. (Hsu et al., 2024)

The next kind of battery is nickel-cadmium, which was invented in 1899 and still used today, mostly in portable home appliances. (Hsu et al., 2024) A nickel-cadmium battery typically consists of a nickel (III) oxide-hydroxide positive cathode and a cadmium negative electrode plate. (Nickel-cadmium battery, 2022) Additionally, nickel is also used in electrode materials widely, in batteries such as NCA, which will be discussed further in this paper. Nickel-cadmium batteries have a long life and are the most economical rechargeable batteries, but the materials used in the batteries, especially cadmium, are detrimental to the environment and several countries have restrictions in place for the use of these substances. (Hsu et al., 2024)

Lithium-ion batteries are currently the most used ones, and they will be discussed further in the next chapter, however, let us explore how Lithium ions came to dominate the energy storage market in terms of batteries. Lithium has the lowest atomic weight (6.95 u) and the lowest density (0.534 g/cm^3)among all metals, it was discovered in 1817 by Johan August Arfwedson. (Winter, Barnett and Xu, 2018) Lithium also has the lowest reduction potential of any element, which allows batteries to have the greatest possible cell potential. (Nitta et al., 2015) This is true because energy of a battery cell is proportional to cell voltage, which is the difference between cathode and anode potentials. (Winter, Barnett and Xu, 2018)

Sodium sulfur batteries are a field of interest and have attracted great attention in recent years, in 2017, an article titled "Progress and prospects of sodium-sulfur batteries: A review" was published and I will summarize the key points made in this paper. Sodium-sulfur batteries are high temperature batteries, made to operate at around 300 degrees Celsius, they consist of liquid sodium, serving as the negative electrode, a solid electrolyte, and liquid sulfur in the outer container serving as a positive electrode. Beta-Alumina solid electrolyte membrane selectively allows positive sodium ions to pass through while restricting electrons, avoiding self-discharge. One challenge which presents itself when considering these batteries is the possible interaction of sodium and sulfur due to a failure of the solid electrolyte in preventing contact between the anode and cathode, which can cause a fire or explosion. Further challenges are discovered when these batteries are considered for room temperature operations. (Kumar et al., 2017)

Sodium ion battery research is another field which seems to promise great potential and has researchers intrigued by its capabilities, not only in the academic field, but also in the industrial world. (Cai et al., 2024) The working mechanism of Li-ion batteries in which charge carriers shuttle between the cathode and anode applies to sodium ion batteries too, and they are both alkali metals. (Cai et al., 2024) While lithium mining and extraction poses environmental threats and lithium scarcity will lead to shortages in the future, sodium, on the other hand, is cost effective and is the 4^{th} most ample element in Earth's crust. (Suntharam et al., 2024)

The sodium/nickel chloride cell works much like the sodium sulfur battery discussed earlier, consisting of a liquid sodium negative electrode separated from a nickel chloride positive electrode by a sodium-ion conducting solid electrolyte, beta alumina. (Sudworth, 2001) The major advantage this battery holds is its safety, the sodium/nickel chloride battery passed crash tests, overcharge test, over-discharge test, vibration test, short circuit test, water submersion test because it has a four barrier safety concept which ensures that under most circumstances, the battery would not pose a safety risk to the people or the environment. (Dustmann, 2004) According to another paper, published in 2015, sodium chloride technologies are fully mature for large scale electrochemical energy storage due to their high safety features, the paper also highlights the applicability of these batteries in stationary energy storage such as renewable energy facilities. (Benato *et al.*, 2015)

Zinc bromine batteries, zinc bromine redox flow batteries (ZBRFB) or zinc bromine flow batteries (ZBFB) are also one of the types that have been under heavy development and research, not unlike those described earlier. This battery is of particular interest because of zinc's abundance on Earth, the battery's tunable power, its cost-effectiveness and its long-life cycle. (Han and Shanmugam, 2024) Additionally, 100% discharge of the battery improves its performance as opposed to harming it, as is the case with many current batteries. (Khan *et al.*, 2024) Of course, this battery also has many drawbacks including expansion of the battery due to bromine gas production and polybromide migration to the Zn anode, development of hybrid materials for these batteries is crucial for large-scale energy storage uses. (Han and Shanmugam, 2024) Fig11 explains the working mechanism of Zinc bromine redox flow batteries, where the bromine ions balance the positive zinc ions in the discharge process to release energy. A diagram is shown because this is the first flow battery discussed in this paper, which possesses a different working principle than those previously mentioned.

The next battery type, polysulfide-bromine flow battery is yet another which utilizes the redox flow principle just discussed. It employs aqueous sodium polysulfide and sodium bromide as the anolyte and catholyte, respectively. (Zhang, 2015) This battery presents a low-cost solution if expensive bromine complexing agents are not employed, however, this battery uses electrolytes containing varying types of active elements which can result in numerous complications if cross-contamination were to occur,

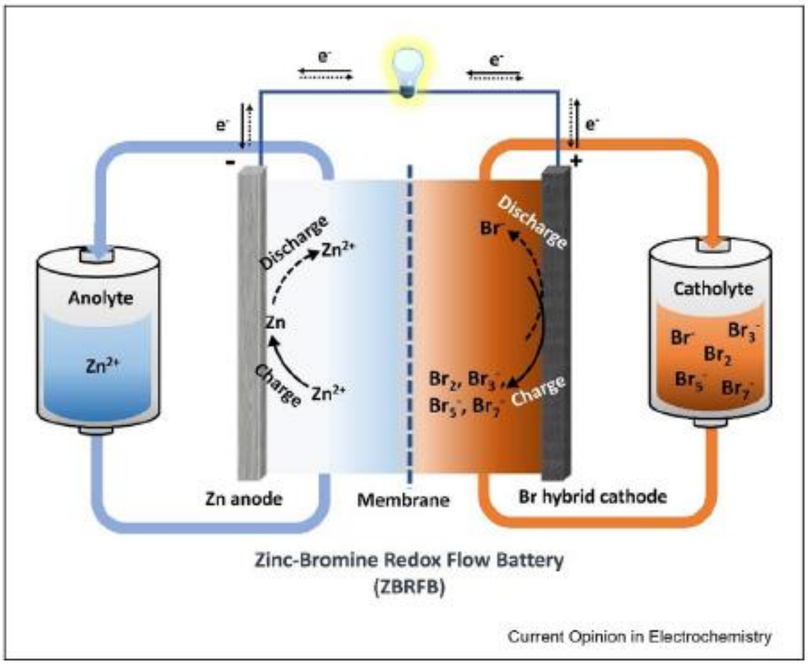

Figure 11 Working mechanism of a zinc-bromine redox flow battery (Han and Shanmugam, 2024)

another problem is the environmental risk posed by possible bromine and hydrogen sulfide contamination. (Zhang, 2015)

In recent decades, Vanadium Redox Flow Batteries (VRFB) have garnered significant acclaim, partially due to vanadium's exhibition of four oxidation states ($V^{2+}, V^{3+}, VO^{2+}, VO_2^+$). (Chitvuttichot, Yeetsorn and Tuantranont, 2024) During discharging, the negative electrolyte is oxidized from V^{2+} to V^{3+}, while the positive electrolyte is reduced from VO_2^+ to VO^{2+}, the inverse process takes place during charging. (Lourenssen *et al.*, 2019) VRFBs present a low probability of explosion and are comparatively more environmentally friendly in contrast to lead-acid and li-ion batteries. (Chitvuttichot, Yeetsorn and Tuantranont, 2024) Some of VRFBs' drawbacks are their high cost, limited energy density within the electrolyte and degradation within the cell because of the severe environment created by the sulfuric acid and vanadium species. (Lourenssen *et al.*, 2019)

2.3.3 Batteries Relevant to the Research

So far, I have explained briefly the working principle of the most well-known battery types, along with some of their advantages and disadvantages. However, I now must delve more deeply into the battery types that are to be studied in this paper. Therefore, in the next sections I will describe sufficiently NMC, LFP and NCA batteries, and then $Li_{10}GeP_2S_{12}$ (a sulfide-based solid-state battery) and LLZO (oxide-based solid-state battery). My choice of batteries for solid-state batteries was based on literature availability, as for my choice of NMC, LFP and NCA, I based it on two articles, one news article written in 2022 naming these three batteries as the most widely used in electric vehicles(Agatie, 2022) and another scientific article published in 2020 which names these three batteries as the ones who share the top spots in electric vehicle batteries. (Jones, Elliott and Nguyen-Tien, 2020) Please note that in conventional batteries, during discharging, electrons move from the anode to the cathode, this process is then reversed during charging, with the electrons moving towards the anode.

NMCs, LFPs and NCAs are cathode active materials, and they will be the focus of the assessment of lithium-ion batteries, that is because graphite has dominated the anode market since the introduction of lithium-ion batteries due to its exceptional attributes, including its low cost, abundance and long cycle life. (Zhang *et al.*, 2021) Electrolytes employed in lithium-ion batteries consist of an ion-conducting lithium salt, such as hexafluorophosphate dissolved in a carbonate-based solvent such as dimethyl carbonate or sulfone-based organic solvent like dimethyl sulfite. (Daems *et al.*, 2024)

The first cathode active material to be studied is NMC batteries which refers to Nickel, Manganese and Cobalt respectively, this battery may alternatively be called MNC and is available in different ratios of these elements. The original NMC ratio was NMC-111, but after thorough research, it was discovered that nickel’s advantageous qualities would benefit energy density, resulting in NMC-811 and NMC-532 among others. (Greenwood, Wentker and Leker, 2021)

In NMC batteries, the electrochemical reactions which occur during charging and discharging involve the oxidation and reduction of electrodes. (Evro *et al.*, 2024) The chemical equations below represent these reactions.

During charging:

$$LiNiMnCoO_2 \rightarrow NiMnCoO_2 + Li + e^-$$

(1)

(Evro *et al.*, 2024)

During discharging:

$$NiMnCoO_2 + Li + e^- \rightarrow LiNiMnCoO_2$$

(2)

(Evro *et al.*, 2024)

NMC 111 commercial batteries usually have a specific capacity of 170 mAh/g, a volumetric capacity of 600 mAh/cm^3 and average voltage of 3.7 V. (Nitta *et al.*, 2015)

LFP cathode active material is also, as already stated, a very common option in automobiles, each letter denotes Lithium, Iron and Phosphate respectively, it has optimal thermodynamic stability due to strong P-O bond within the phosphate structure. (Evro *et al.*, 2024) The composition of this cathode is typically $LiFePO_4$. (Hemavathi, Srirama and Prakash, 2023)

During charging:

$$LiFePO_4 \rightarrow FePO_4 + Li + e^-$$

(3)

(Evro *et al.*, 2024)

During discharging:

$$FePO_4 + Li + e^- \rightarrow LiFePO_4$$

(4)

(Evro *et al.*, 2024)

LFP commercial batteries have a specific capacity of 165 mAh/g, a volumetric capacity of 589 mAh/cm^3 and an average voltage of 3.4 V. (Nitta *et al.*, 2015)

NCA (Nickel Cobalt Aluminum Oxide) batteries have a chemical composition of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, utilizing aluminum instead of manganese, as is done in NMC, for enhanced stability. (Hemavathi, Srirama and Prakash, 2023) NCAs have a high discharge capacity and low self-discharge rate, though there are reports that capacity fade can be extreme at high temperatures. (Nitta *et al.*, 2015)

During charging:

$$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2 \rightarrow Ni_{0.8}Co_{0.15}Al_{0.05}O_2 + Li + e^- \tag{5}$$

During discharging:

$$Ni_{0.8}Co_{0.15}Al_{0.05}O_2 + Li + e^- \rightarrow LiNi_{0.8}Co_{0.15}Al_{0.05}O_2 \tag{6}$$

Commercial NCA batteries have a specific capacity of 200 mAh/g and a volumetric capacity of 700 mAh/cm^3 and an average voltage of 3.7 V. (Nitta *et al.*, 2015)

After discussing the properties of traditional Li-ion batteries, I will now discuss the attributes of SSBs. Solid State Batteries utilize solid materials as electrolytes for transporting lithium ions from the cathode to the anode and vice versa, they can also achieve higher energy densities by using metal lithium anodes. (Liu *et al.*, 2024) Solid state batteries are set to overcome the safety issues inherent to liquid electrolyte batteries such as fire and leakages, additionally, they have higher energy densities also due to the reduction in volume from liquid electrolytes to solid electrolytes. (Yuan and Yuan, 2024) One important distinction between NMCs, LFPs, NCAs and solid-state batteries is the fact that when discussing the materials used in the former, we were specific to cathodes, while for solid-state batteries, we will be discussing a change in electrolytes for enhanced performance.

The first electrolyte to be examined more closely is the sulfide-based $Li_{10}GeP_2S_{12}$, we will look at the chemical composition of this electrolyte along with the suggested electrode materials thus far, and its electrochemical capabilities. $Li_{10}GeP_2S_{12}$ was discovered in 2011 and it was discovered to possess extremely high ionic conductivity at room temperature, however, despite its favorable qualities, it still faces interface issues when combined with Li metal anodes, whose high theoretical capacity of 3860 mAh/g makes them one of the best candidates for solid-state batteries (SSBs). (Zheng *et al.*, 2023) $Li_{10}GeP_2S_{12}$, or lithium germanium phosphorus sulfide, or LGPS is one of the more favorable candidates for SSBs and recently, a lot of researchers have examined its qualities with different electrodes and various additives to make it compatible with Li metal anodes, however, for the purpose of this article, I will use an experiment performed in 2011, citing their electrode materials and their test results. Using a $LiCoO_2$ cathode, a $Li_{10}GeP_2S_{12}$ electrolyte and an Indium metal anode at a current density of 14 mA/g, the battery was shown to exhibit a discharge capacity of 120 mAh/g and excellent discharge efficiency. (Kamaya *et al.*, 2011) (values reused with permission from the publisher)

The next type of solid electrolyte is the oxide-based LLZO, or lithium lanthanum zirconium oxide, has a chemical composition of $Li_7La_3Zr_2O_{12}$ and is attractive for its high ionic conductivity, high density, mechanical strength and large electrochemical window. (Sun, Kang and Cui, 2023) Unfortunately, as much as this electrolyte might seem like a perfectly suitable material, the formation of Li_2CO_3lithiophobic layer on the LLZO layer when exposed to air hinders its compatibility with molten lithium anodes due to Li_2CO_3's low lithium-ion conductivity and its decomposition at voltages as low as 3.2 V. (Zhang *et al.*, 2022) Therefore, Zhang et al. decided, in their experiment, to turn the unfavorable lithiophobic Li_2CO_3 into a lithiophilic Li_xSiO_y(varying between Li_2SiO_3 and Li_4SiO_4) via double replacement reaction by adding SiO_2 , and modifying LLZO into $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ (LLZTO), the additional element being tantalum for a higher air stability, this electrolyte will be referred to as LLZTO@LSO for abbreviation. Using lithium as the anode, $LiCoO_2$ as the cathode, and LLZTO@LSO as the electrolyte, this battery showed initial charge and discharge specific capacities 151.2 and 135.1 mAh/g at 0.4 C (2.5 hours) respectively, this hybrid solid-state battery exhibited excellent stability and reversibility. (Zhang *et al.*, 2022)

2.4 Environmental Impact of Solid-State Batteries and NMC, LFP and NCA Batteries

2.4.1 Materials and Methods

Since we have so far studied the growth of energy and mankind's focus on electricity and the ways in which this sector grew rapidly, leading to the great demand for batteries in the world, which then led us to discussing the basic features of three of the most commonly used lithium-ion batteries and two of the potential candidates for solid-state batteries, we must now ask whether solid-state batteries are a more environmentally friendly alternative and at what environmental cost do they come compared to their liquid electrolyte counterparts?

Firstly, it is important to note the challenges that arise when one wishes to numerically assess the environmental impact of SSBs, mainly, that is a lack of literature, which is a result of the different chemical compositions in use in their development to tackle problems such as ionic conductivity, interfacial problems and others. According to a paper published in 2023, there were 15,800 hits on Google Scholar, showing only six detailed Life Cycle Assessments (LCAs) on SSBs. (Mandade *et al.*, 2023) I will now describe the papers I wish to use in my research to reach a satisfactory conclusion despite the challenges and discrepancies existent in the rapidly changing field of SSBs.

Starting with SSBs, more specifically $Li_{10}GeP_2S_{12}$ (LGPS), I will use a paper published in 2021 (Tao, Tao and Zhihong, 2021) which assesses the recycling of germanium containing materials and the challenges which accompany it, I found this to be a relevant paper because LGPS batteries are the only batteries pertinent to this paper taking advantage of this element's properties and understanding the environmental burden this causes is essential for the goal of this paper. The second paper I will reference is one written in 2023 (Kreher *et al.*, 2023), tackling the problem of this compound's production, which results in hazardous compounds that can threaten the factory workers' health. The importance of this paper lies in the prospect of the industrialization of this battery and ensuring that whoever takes this step takes this environmental risk into account.

As for LLZTO batteries, I will use two papers, one published in 2021 (Smith *et al.*, 2021), which provides values for the Global Warming Potential of LLZTO (not containing LSO) and another paper published this year (Liu *et al.*, 2024), providing comprehensive comparative analysis of LLZO batteries (not containing tantalum or LSO) in terms of their carbon footprint and water footprint, these values will serve as precursors to predict the environmental impact of these batteries once they are commercially available.

For NMC batteries, I will use a paper published this year (Marashli *et al.*, 2024) providing values for carbon footprint according to different studies across the years. In addition, I will also use a paper also published in 2024 (Gutsch and Leker, 2024), breaking down the cost and carbon footprint of battery production into the different steps of production and into the separate elements involved.

LFP's environmental impact information will be taken from a paper published in 2022 (Quan *et al.*, 2022), comparing the environmental impact of LFP batteries with NMC batteries and provides valuable information such as carbon footprint according to previously published papers. Another paper that will be used for LFPs is one written in 2024 (Picatoste *et al.*, 2024), which shows the circularity of batteries currently used in electric vehicles and provides values such as Global Warming Potential and Abiotic Depletion Potential of minerals (addressing the future availability of a raw material).

Finally, NCAs will be assessed through (Yudhistira, Khatiwada and Sanchez, 2022) comparing different Li-ion batteries' environmental impact in carbon footprint per kWh.

2.4.2 Solid- State Batteries

During the production of sulfide-based solid electrolytes, namely, Li_3PS_4(LPS) and previously mentioned LGPS, a highly toxic and corrosive gas hydrogen sulfide is released which raises concern for the workers' safety. (Kreher *et al.*, 2023) Concentrations of hydrogen sulfide above 1000 ppm can cause unconsciousness and can prove fatal over 5000 ppm, according to the hydrogen sulfide release from reactants in laboratory-scale experiments, upscaling to mass production indicated that without special measures, tolerable hydrogen sulfide concentrations would be exceeded in a short time, therefore, certain measures such as temperature and air exchanges must be taken to ensure the workers' safety. (Kreher *et al.*, 2023) I will not be talking about the exact measures that should be taken since it includes mathematical equations and assumptions made that would require much time, therefore, I think it sufficient to establish that this battery's production requires exceptional environmental health and safety measures. With economic circularity in mind, it is essential to establish the circularity of a material before its industrialization, in (Tao, Tao and Zhihong, 2021), it is shown that some of the problems faced when extracting germanium included high fraction of extractant in organic phase, high stripping temperature, and high concentration of stripping reagent. One example of the severity of these problems is the fact that approximately one percent of the total germanium mined with coal could be transformed into refined germanium. (Tao, Tao and Zhihong, 2021)

SSBs containing LLZTO electrolyte exhibited a Global Warming Potential(GWP) of 43.76 kg CO_2-equivalent per 50 MJ or 13.9 kWh of electrical energy compared to 1.6 kg CO_2-equivalent produced by Li-ion batteries according to the paper, the difference becomes even greater when the GWP is calculated per kg of battery, which is 79.11 kg CO_2-equivalent and 22.97 kg CO_2-equivalent for SSBs and Li-ion batteries, respectively. (Smith *et al.*, 2021) According to the paper, the discrepancy between the two batteries when using 50 MJ as the functional unit can be partially accounted for by the assumed cycle life of the batteries, due to the lack of commercialized SSBs, it is difficult to estimate the number of cycles the battery can serve, however, this paper indicates that researchers need to focus on reducing the environmental impact of SSB technology. (Smith *et al.*, 2021) The paper (Liu *et al.*, 2024) assesses the carbon and water footprint of LLZO batteries in contrast to others, of which I will include NMC and LFP batteries, the results are shown in the table below. (Liu *et al.*, 2024)

Table 1 Carbon and Water Footprints of LLZO, NMC and LFP (my own work with the values from Liu et al., 2024)

Battery	Carbon Footprint per kg of Battery (unit: kg CO_2-equivalent)	Water Footprint per kg of Battery (unit: m^3)	Carbon Footprint per 1 kWh (unit: kg CO_2-equivalent)	Water Footprint per 1 kWh (unit: m^3)
LLZO	41.12	13.85	132.65	44.68
NMC	8.98	5.69	59.87	37.93
LFP	13.08	7.36	148.64	83.64

As can be seen by the values given above, LLZO performed worse than both LFPs and NMCs when the functional unit was 1 kg of battery, however, when the functional unit was changed to 1 kWh, LLZO performed better than LFP batteries, but NMC batteries remained the better option throughout. However, the mining of nickel has led to environmental implications such as acidification, heavy metal contamination and a reduction in biodiversity. (Smith *et al.*, 2021)

2.4.3 NMC, LFP and NCA

In 2024, a study was conducted using NMC-811 batteries produced by the Tesla Gigafactory established in Nevada and the carbon footprint was found to be 1823.5 kg CO_2-equivalent per 114 kg (weight of the battery) or around 16 kg CO_2-equivalent per kg, with mining and production accounting for 68.78% of the carbon footprint. (Marashli et al.,2024) Another study in 2024 established that NMC-811 batteries exhibit a global warming potential of 64.5 kg CO_2-equivalent per kWh. (Gutsch and Leker, 2024)

In 2022, a study found that the global warming potential of LFP batteries in the production phase is 76.7 kg CO_2-equivalent per kWh, and LFP batteries also showed highest GWP during secondary use, at 441 kg CO_2-equivalent per kWh, much greater than NMC's 181 kg CO_2-equivalent per kWh. (Quan *et al.*, 2022) A study in 2024 also examined the different recycling methods available and their GWP, LFP batteries undergoing pyrometallurgy recycling show a GWP of 0.6 kg CO_2-equivalent per kWh but when considering resource extraction, LFP batteries perform better than NMC batteries, the GWP being 116 and 85 g CO_2-equivalent for NMC and LFP batteries, respectively. (Picatoste et al., 2024) I will not consider recycling values when comparing SSBs with traditional Li-ion batteries because of a lack of information regarding the circularity of SSBs.

Finally, the last battery type to be considered is NCA, whose GWP is calculated and then compared to existing literature, the values being 115 and 113.9 kg CO_2-equivalent per kWh respectively, this shows there is not much deviation, according to the existing literature, NMC and LFP exhibit GWP of 104 and 169 kg CO_2-equivalent per kWh. (Yudhistira, Khatiwada and Sanchez, 2022)

3. Materials and Methodology

So far, this study has discussed the origin of energy and the focus of efforts on harnessing electricity to a usable form. We then also delved into the fast-paced growth of electricity and the rise in demand for this commodity. After that, electric vehicles grew to become a great market which hence increased the need for batteries. Development in this field has grown significantly over the past decades and the basic features of different battery types were covered, followed by the environmental impact of these batteries.

To sufficiently understand and compare these batteries' environmental impact, I must first constrict myself to one parameter that is most commonly found among all the batteries I mentioned in the previous section. The GWP previously mentioned was referring to the carbon footprint of the production process of the respective batteries. Despite the fact that this quantity is not available for LGPS electrolyte batteries, it is available for LLZTO and LLZO batteries, still allowing us to compare two different solid-state batteries' GWP with the rest of the batteries. Therefore, my comparison will be built on the GWP per kWh during the production of the batteries, as given by the literature cited above.

To ensure higher accuracy, I will calculate the average for all the carbon footprint values found in the papers, for example, NMC batteries have four values listed across the different papers considered (of which only two where the chemical composition was explicitly mentioned and hence can be relied on), so before assessing this battery's values, I will calculate the average value. It should be said that some of the values vary due to the presumed cycle life, secondary reuses, recycling and repurposing, some of which are implemented by companies. However, once the four values are considered, the mean will be a relatively reliable number for further comparison.

After the different average values are determined for NMC, LFP, NCA, LLZO, LLZTO batteries, I will use Microsoft Excel to show the differences graphically.

4. Results and Discussion

The first step I will take is to display all the values collected by the papers and highlight the values which will be excluded from consideration due to the composition of the cathode being not completely clear. On the same table, I will include the average value without the highlighted cells.

Table 2 Containing the values which will be used in the following comparisons (excluded values are highlighted)

Battery Type	GWP (kg CO_2-equivalent) per kWh				Average
NMC	59.87	64.5 (NMC-811)	16 (NMC-811)	104	40.25
LFP	148.64	76.7	169		131.45
NCA	115	113.9			114.45
LLZO	132.65				132.65
LLZTO	608.264 (might be affected by the estimated cycle life)				608.26

Table 3 Containing the battery types and calculated average

Battery Type	GWP (kg CO_2-equivalent) per kWh
NMC	40.25
LFP	131.45
NCA	114.45
LLZO	132.65
LLZTO	608.26

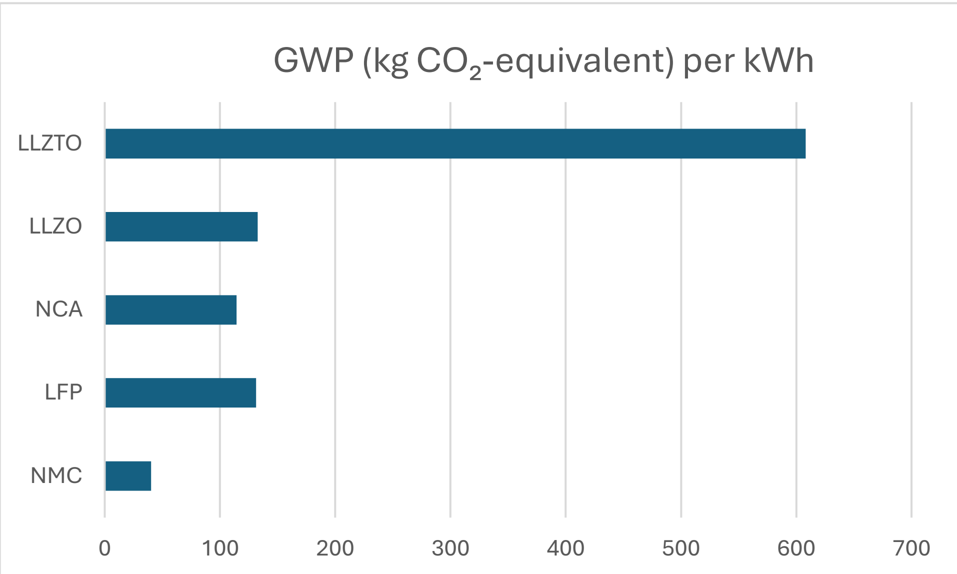

Figure 12 GWP of different batteries in the production phase

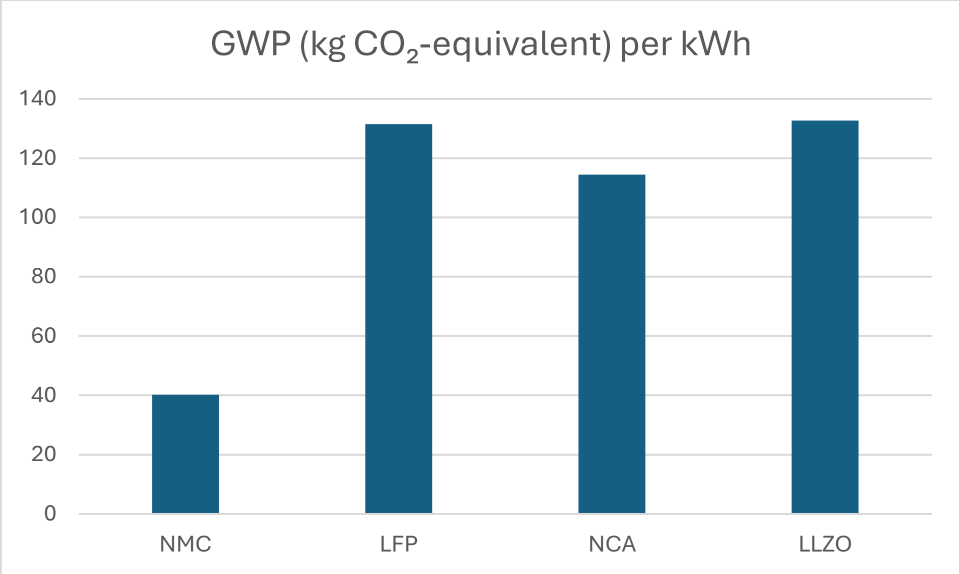

Figure 13 Battery types and GWP during production without LLZTO

As can be seen by the figures above, when the functional unit is taken as kilowatt hour, which is essentially the energy needed to power a one-thousand-watt (Watt is a unit of power) appliance for one continuous hour, NMC batteries perform better than all the batteries considered. However, other environmental concerns such as the effects of mining nickel and cobalt are not easy to account for using only the GWP as a metric and as mentioned previously, nickel mining is especially detrimental because of acidification and loss of biodiversity. (Smith et al., 2021) LLZO batteries performed close to NCA batteries and have a lower carbon footprint than LFP batteries.

5. Conclusions and Suggestions

After exploring the potential of SSBs in terms of future battery chemistries due to their high specific capacity and their incredible safety features, we ventured to assess the potential environmental impact they could exact once industrialized. Despite some literature available, I must declare that the results shown in this research are not as of yet extensive enough to be used as a standard since research is still ongoing, and the potential chemical compositions being thoroughly tested and experimented with comprise a list that is too long to include in my paper. However, for the SSBs and other commercial li-ion batteries chosen for this research, the results indicate that some solid-state batteries (LLZO) possess a lower carbon footprint than some of the more common batteries (LFP).

Since SSBs are not yet commercially available, such data is scarce and thus might affect the measurement of carbon footprint. Overall, these results indicate that some challenges in the development of SSBs are yet to be tackled in terms of their environmental impact. In addition, more analyses concerning SSBs cycle life and other factors must be done to be able to better numerically understand the attributes and capabilities of such batteries. The SSBs considered in this section are seen to be generally more potent threats to the environment in terms of GWP than their liquid electrolyte counterparts (especially NMC), but that may also be because recycling, secondary uses and cycle life played a role in diminishing these batteries' carbon footprints since some of the cited papers took that into account.

Additionally, LGPS has drawbacks aside from their carbon footprint, which was unfortunately not included in the scope of this paper, such as the hazardous environment that is created due to their release of fatal gases that must be monitored and may require more effort to establish a production line, additionally, retrieving germanium may prove to be an issue according to some research.

Through my research, where my goal was to find a reliable method to roughly imagine how the environment would be affected by the potential industrialization of SSBs by taking the models which exhibit high potential and examining the available researches for these batteries' carbon footprint and other metrics such as mining risks and ability for these batteries to be incorporated into a circular economy, I was able to determine how this field could be further developed. These suggestions, which are based on the current literature that I was able to access and study, and therefore may be missing progress done by commercial companies that is not available to the public and they are as follows:

- More Life Cycle Assessments (LCAs) must be completed on SSBs considering different cycle lives and chemical compositions. These must be completed and presented numerically to provide a more lifelike perspective on the projected effect of SSBs once they become available.

- Issues such as ionic conductivity and interfacial stability need to be improved for SSBs to be considered as an alternative to the already available batteries, this is already being done in many locations around the world and is growing at a rapid rate, indicating that the most efficient solution might become apparent soon.
- Recycling conditions and processes must be established and used to standardize the SSBs to be industrially produced. This is a necessity because the variety in li-ion batteries currently available presents a myriad of issues and obstacles when considering recycling facilities since a process must be tailored for each battery type that the facilities receive. These challenges can be avoided before the spread of SSBs easier than later when SSBs become waste products around the world.

Based on the direction in which research facilities are headed, all the issues mentioned will be addressed soon, and this can potentially expedite the process of commercialization for SSBs.

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7. List of Figures/Tables