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MOBILITY BASED ON LITHIUM-ION BATTERIES, AN OVERVIEW

Abstract. Climate change and air pollution increasingly affect people and the natural environment. Among the major sources of greenhouse gases and air pollutants are transport, especially road transport. In order to reduce the dependence on fossil fuels in the transport sector, electric vehicles, which mainly use lithium-ion batteries, have been increasingly promoted. The development of electric mobility is not without challenges, including the supply of critical raw materials, environmental impacts during the life cycle or the cost of batteries. Although they are not entirely ecological, electric vehicles have a lower impact on the climate compared to conventional vehicles. Widespread use of renewable energy sources will further reduce this impact. The research results show a significant increase in sales of electric vehicles in recent years, but a fairly high concentration of lithium reserves (and other raw materials needed for lithium-ion batteries) and battery production. Electric vehicles can contribute to the decarbonisation of transport and all efforts, including research and development, should be intensified to support them and identify the best solutions to current challenges.

Keywords: climate change, electric mobility, lithium, lithium-ion batteries, environmental effects

1. Introduction

According to NOAA (2024), 2023 was the warmest year since the institution has been taking climate measurements (1850-2023). And it is not an exception. The warmest 10 years were recorded in the last decade. In 2023, the global average temperature exceeded the pre-industrial average (1850-1900) by 1.35°C. The planet is warming, and the impact of climate change can be very costly for people and the natural environment. Many effects of climate

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change are already visible, such as the melting of glaciers, rising sea levels or the intensification of extreme climate events. Since the current climate changes are due to anthropogenic emissions of greenhouse gases, urgent measures are needed to significantly reduce them.

One of the major sources of greenhouse gases, with approximately 15% of global emissions, is the transport sector (IEA, 2023a). Transports also affect the environment and human health through various pollutants: nitrogen oxides, suspended particles, carbon monoxide or hydrocarbons. In recent years, electric vehicles have been promoted as a solution to this problem, as they can reduce environmental impact, especially when powered by electricity from renewable energy sources (Notter et al., 2010, Faria et al., 2013, Hawkins et al., 2013, Bauer et al., 2015). Thus, the number of electric vehicles sold worldwide has increased considerably, exceeding 10 million units in 2022, i.e. 14% of total vehicle sales (IEA, 2023a).

There are three categories of vehicles that use energy stored in batteries: all-electric vehicles, plug-in hybrid electric vehicles (they use an internal combustion engine and an electric motor), and hybrid electric vehicles (they use an internal combustion engine and one or more electric motors, and the energy stored in the battery is done by regenerative braking).

Currently, the vast majority of electric or hybrid vehicles use lithium-ion batteries, due to their higher energy density, high energy efficiency, good performance at high temperatures, longer service life, low self-discharge rate or lighter weight, compared to other electrical energy storage systems. A lithium-ion battery used by electric vehicles comprises three main components: the cells, which contain the active materials, the battery management system (which controls the performance and safety of the battery), and the pack, which is the structure in which the cells are assembled, usually with a cooling system, insulation material, electrical connections and housing (Melin, 2019). Inside each cell, lithium atoms move through an electrolyte between a graphite anode and a cathode. Cathodes are usually one of the most expensive parts of a battery, and a type of cathode called NMC (nickel manganese cobalt) is dominant in electric vehicle batteries today. Lithium iron phosphate batteries using a cheaper cathode have increased their share recently, reaching about 40% in 2022 (MIT Technology Review, 2023). Another alternative to lithium-ion batteries would be sodium-ion batteries, as sodium is more abundant and less expensive than lithium (Hwang et al., 2017). However, this promising technology is in the early stages of development.

This research proposes a current analysis of the transport sector based on lithium-ion batteries. It aims to identify all the challenges facing electric mobility, from the supply of mineral resources, the concentration of production, the evolution of production costs to the environmental impact during the life cycle.

2. Materials și methods

The present research uses quantitative and qualitative methods to collect and analyze data on lithium-ion battery-based mobility, as well as challenges regarding its future evolution. The statistical data used in the research come from international sources and databases (International Energy Agency, Energy Institute, International Lithium Association, Statista or World Economic Forum), but also from consulting a specialized bibliography and other sources. In order to highlight the evolution of some indicators, such as global lithium production or sales of electric vehicles, graphical methods were used which were subsequently interpreted.

Scenarios and estimates for the future evolution of demand for lithium and other critical minerals required for lithium-ion batteries and battery production capacity were based on data published in 2021 by the International Energy Agency and on estimates by the World Economic Forum, McKinsey&Company and S&P Global. The role of lithium-ion batteries in the global effort to combat climate change and its negative effects on the environment has been based on a number of scientific articles published in various journals and other sources. In general, the examination of the current state of electric mobility based on lithium-ion batteries and development challenges were based on specific analytical research.

3. Results

3.1. Lithium reserves and production

Lithium plays a key role in most of the batteries currently used to equip electric vehicles. On average, an electric car uses 8.9 kg of lithium (IEA, 2021). Lithium is the lightest and most reactive of the alkali metals. Being highly reactive, lithium is never found in its pure state in nature. It is found in the earth's crust in igneous rocks such as pegmatite. Spodumene is the most important lithium-bearing mineral in terms of production, being the main source of lithium for the production of lithium carbonate until the mid-1990s. Lithium is also found in the brines of some closed basins in mountainous regions (such as the Andes), the brines of some oil and geothermal fields or clay minerals (hectorite is a lithium-magnesium-sodium montmorillonite that typically contains 0.3–0.6% lithium). Seawater contains lithium, but in very low concentrations. The earth's crust contains on average about 20 ppm lithium (0.0020%), while seawater typically contains 0.18 ppm lithium (0.000018%) (International Lithium Association, 2023a).

Thanks to continuous exploration, in recent years lithium reserves have been identified all over the world (Figure 1). South America holds the largest lithium reserves discovered to date, mostly in Chile, Argentina and Brazil. Large reserves have also been identified in Australia, China, the United States and Zimbabwe. Lithium reserves have also been discovered in Bolivia, Canada, Mexico, Peru, Namibia, South Africa, Congo Kinshasa, Mali, Germany, Czech Republic, Serbia or Russia (Shaw, 2021, Energy Institute, 2023).

At the end of 2022, the largest lithium reserves were in Chile (9.3 million tonnes), i.e. 40.4% of the world total. Australia (6.2 million tonnes), Argentina (2.7 million tonnes), China and the United States were next (Figure 2). Total reserves were estimated at 23 million tonnes (Energy Institute, 2023).

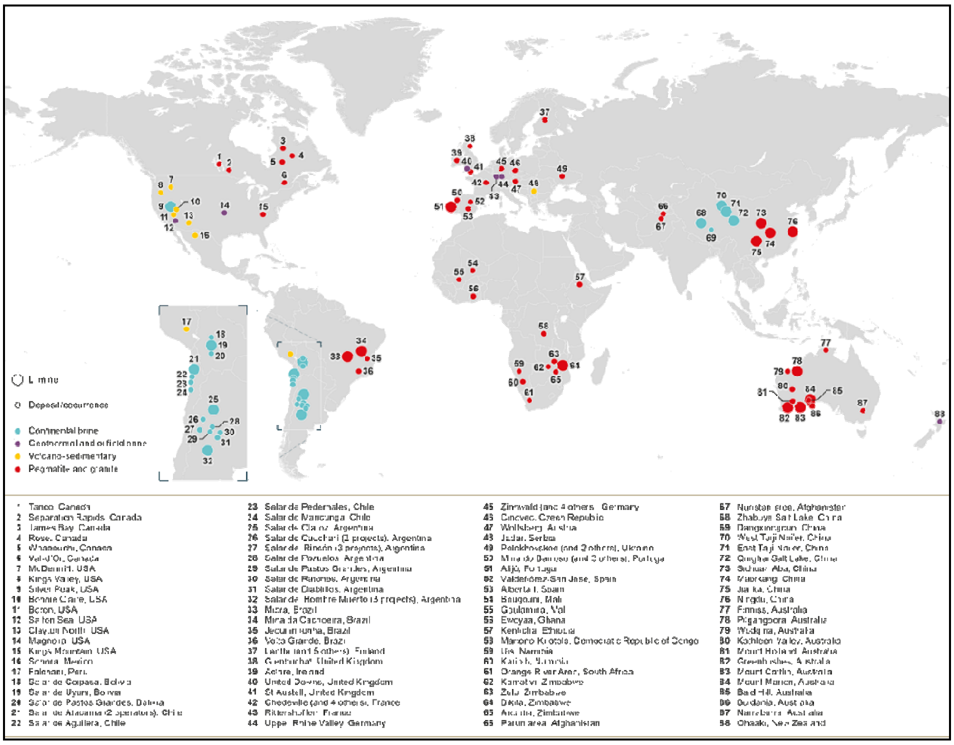

Figure 1. Global lithium mines, deposits and occurrences
(*Source:* Shaw, 2021)

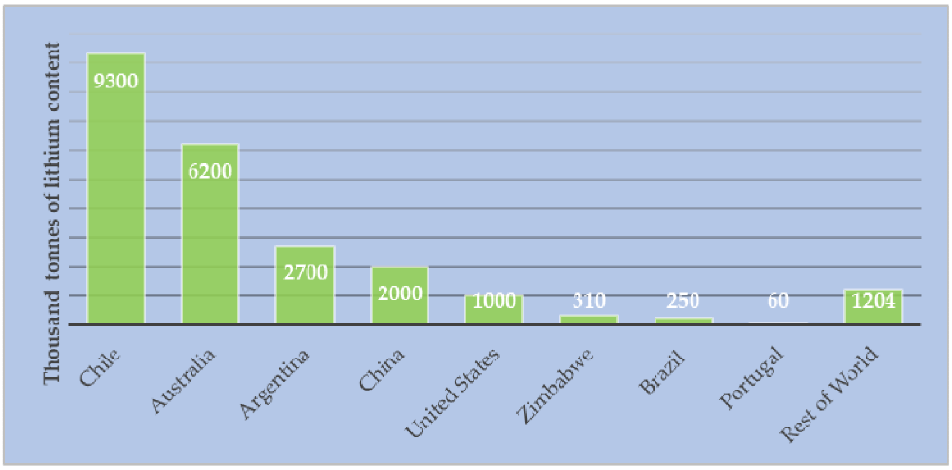

Figure 2. Reserves of lithium worldwide at the end of 2022, by country
(*Source:* Energy Institute, 2023)

As lithium plays a key role in batteries, the increase in demand for electric vehicles has driven lithium production to new heights. Global lithium production exceeded 100,000 tonnes for the first time in 2021 (540,000 tonnes of lithium carbonate equivalent), four times more than in 2010 (Figure 3). In 2022, more than 130,000 tonnes of lithium were produced globally (Energy Institute, 2023). This is a significant increase from 2010, when global lithium production was only 28,100 tonnes (Statista, 2023a).

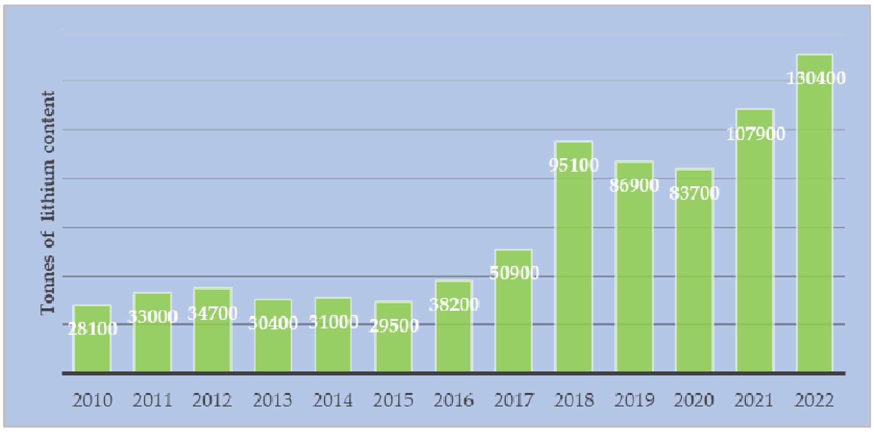

Figure 3. Mine production of lithium worldwide from 2010 to 2022
(*Source:* Energy Institute 2023)

In 2022, more than 90% of production came from just three countries, Australia, Chile and China (Table 1). Australia produced almost 47% of global lithium production in 2022, and more than 90% of Australia's lithium exports were to China. From the 1990s to 2010, Chile was the largest producer of lithium, with the Salar de Atacama being one of the richest lithium brine deposits in the world.

China is the world's third largest lithium producer and controls 60% of global lithium refining capacity for batteries. In addition to developing domestic mines, Chinese companies have acquired about $5.6 billion worth of lithium assets in countries such as Chile, Canada and Australia over the past decade. In the 1990s, the US was the largest producer of lithium, in stark contrast to today. The share of US lithium production has declined from 37% in 1995 to below 1% in 2022 (Energy Institute, 2023, World Economic Forum, 2023).

Table 1

The largest lithium producers in 2022

Rank	Country	2022 Production (thousand tonnes)	Share 2022 (%)
1	Australia	61.0	46.8
2	Chile	39.0	29.9
3	China	19.0	14.6
4	Argentina	6.2	4.8
5	Brazil	2.2	1.7
6	Statele Unite	0.9	0.7
7	Zimbabwe	0.8	0.6
8	Portugal	0.6	0.5
9	Rest of world	0.6	0.5
	Total	130.4	100

(*Source:* Energy Institute, 2023)

3.2. Production of lithium-ion batteries

Although lithium is used in a wide variety of other applications (eg: ceramic and glass production, lubricants, air treatment, aluminum smelting, production of iron and steel castings, production of aluminum-lithium alloys or pharmaceuticals), over 70% of lithium is used in the production of batteries for electric and hybrid vehicles, mobile phones, laptops or for storing energy from renewable sources (USGS, 2023, World Economic Forum, 2023).

Table 2

Applications where lithium is used

End-use	Lithium consumption in 2010 (%)	Lithium consumption in 2021 (%)
Batteries	23	74
Ceramics and glass	31	14
Lubricating greases	10	3
Air treatment	5	1
Continuous casting	4	2
Other	27	6

(*Surces*: World Economic Forum, 2023)

Before electric vehicles increased demand for lithium, the end uses of the metal were completely different than they are today. In 2010, ceramics and glass accounted for the largest share of lithium consumption, with 31% (Table 2).

The first rechargeable battery using lithium (along with titanium) was first developed in the 1970s by English chemist Stanley Whittingham. Later, in 1980, American scientist John B. Goodenough developed a lithium-cobalt battery with increased energy density. The third key breakthrough in lithium battery technology came in 1985, when Japanese chemist Akira Yoshino developed a stable, reliable, and high-power lithium-ion battery that was commercialized by Sony in 1991. In 2019, John B. Goodenough, Stanley Whittingham and Akira Yoshino were awarded the Nobel Prize in Chemistry for their work developing lithium-ion batteries (International Lithium Association, 2023b).

Currently, the lithium-ion battery market is dominated by China (Table 3). In the first half of 2023, Chinese battery giant CATL ranked first in the world in battery production with a share of 36.8%, according to a report by SNE Research (Kang, 2023). If BYD's 16% share is included, the two Chinese companies account for more than half of the electric car battery market.

Table 3

Top battery manufacturers for electric vehicles in 2023

Rank	Manufacturer	Country of origin	Global market share (%)
1	Contemporary Amperex Technology (CATL)	China	36.8
2	BYD	China	15.7
3	LG Energy Solution	South Korea	14.5
4	Panasonic	Japan	7.5
5	SK On	Japan	5.2
6	China Aviation Lithium Battery	China	4.3
7	Samsung SDI	South Korea	4.1
8	EVE Lithium Energy	China	2.2
9	Guoxuan High-tech	China	2.1
10	Sunwoda	China	1.5

(*Source*: SNE Research (cited by Kang, 2023)

As of March 2023, global lithium-ion battery production capacity was around 2.8 TWh. China held over 73% of capacity (over 2 TWh), more than 10 times that of the United States (187.3 GWh), the second largest producer. Other major producers were: Germany (150.8 GWh), Poland (90 GWh), Hungary (57.3 GWh) and Japan (48.1 GWh), then South Korea, France and Sweden, Canada and India (Statistics 2023b).

As a result of the increasing demand, it is estimated that by 2030 the production capacity of lithium-ion batteries will reach 4.7-6.5 TWh, and the demand from the electric vehicle sector will reach 3.7-4.3 TWh (McKinsey, 2023, S&P Global, 2023). China will have more than half of the market share, followed by North America and Europe, each with more than 1 TWh of capacity. This is also favored by a shift in regulations towards sustainability, including Europe's "Fit for 55" program, the US Inflation Reduction Act, the 2035 ban of internal combustion engine vehicles in the EU, and India's Faster Adoption and Manufacture of Hybrid and Electric Vehicles Scheme.

In February 2023, the EU approved a plan requiring all new cars sold in the region to be zero-emissions from 2035 to meet its 2050 climate neutrality goal, which will accelerate the shift to electric vehicles. The EU also plans to source nearly 90% of its battery needs from EU battery manufacturers such as Sweden's Northvolt AB, France's Automotive Cells Company SE or Italy's Italvolt. With just over 400 GWh of capacity planned by 2030, Germany will be the largest battery producer in the region. Northvolt AB will be the largest producer in Europe with an estimated output of 210 GWh from five plants, two in Germany and three in Sweden (S&P Global, 2023).

3.3. Electric vehicles

In the last decade, there has been a significant increase in the number of electric vehicles on the world's roads (Figure 4). If in 2011 around 48,000 electric light-duty vehicles (including plug-in hybrid electric vehicles) were sold, in 2022 their number exceeded 10 million, an increase of 55% compared to 2021. About 14% of all new cars sold in 2022 were electric vehicles. In just five years, from 2017 to 2022, sales of electric vehicles increased from about 1 million to more than 10 million. Regarding the stock of electric vehicles, in 2022 it exceeded 26 million (of which 30% plug-in hybrid electric vehicles), increasing by 60% compared to 2021.

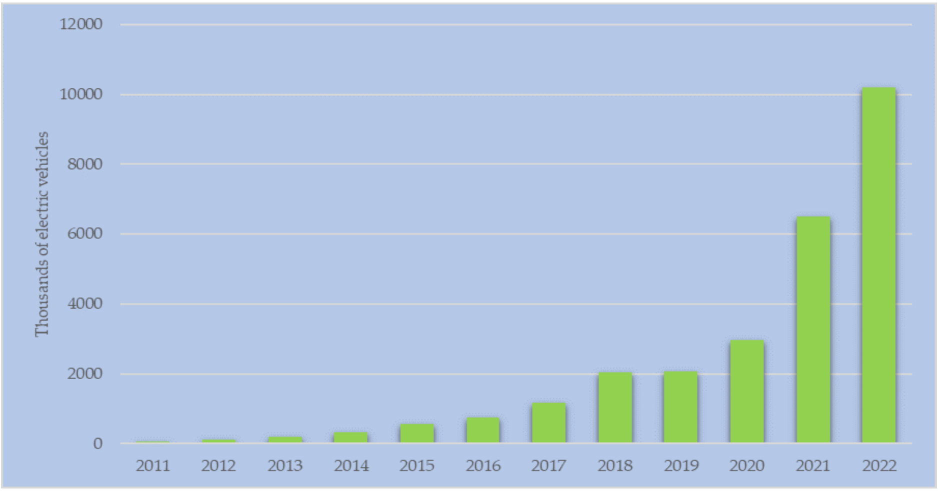

Figure 4. Sales of electric light-duty vehicles (including plug-in hybrid electric vehicles) in the period 2011-2022
(*Source:* IEA, 2023c)

In 2022, about 60% of global electric vehicle sales took place in China (5.9 million, of which 1.5 million plug-in hybrid electric vehicles). In this country, the share of electric vehicles in total domestic car sales has reached 29%. China is also home to more than half of the global stock of electric vehicles.

Europe is the second largest market, with around 2.7 million electric vehicles sold in 2022 (up 15% from 2021). About 21% of cars sold in Europe were electric vehicles, but in some countries the share was much higher: Norway (88%), Sweden (54%), Netherlands (35%), Germany (31%). In terms of volume, the highest sales were in Germany (830,000 units), followed by the United Kingdom (370,000) and France (330,000). In some countries (Italy, Austria, Denmark or Finland) sales of electric cars have decreased or stagnated. Overall, Europe has 30% of the global stock of electric vehicles.

In 2022, the US was the third largest market, with electric vehicle sales growing 55% over 2021, with a sales share of 8%. The total stock of electric cars has reached 3 million, accounting for 10% of the global total.

In 2022, many electric vehicles with two or three wheels were also sold, especially in developing countries. Total sales of electric two-wheelers totaled approximately 9.2 million units, of which 7.7 million were in China (85% of global sales). More than 775,000 electric three-wheelers were also sold, nearly 99% of them in India and China. Also sold were 310,000 electric light commercial vehicles (almost double from 2021), nearly 66,000 electric buses and 60,000 electric medium and heavy trucks. China dominates sales of electric trucks and buses, with around 80% and 85% of global sales, respectively. In addition, many of the buses and trucks sold in Latin America, North America and Europe are Chinese brands (IEA, 2023b).

4. Discussion

4.1. Supply of critical minerals

As a result of the growing demand for lithium-ion batteries, one of the future challenges is the supply of critical mineral resources such as lithium, cobalt or nickel and their price volatility. Estimates of future lithium demand depend on several variables, such as recycling potential, widespread public acceptance of electric vehicles, technological developments (including alternative technologies), or political support for conversion to lithium-ion battery-powered engines. The World Economic Forum (2023), estimates that lithium demand will reach 1.5 million tonnes of lithium carbonate equivalent by 2025 and over 3 million tonnes by 2030.

According to several scenarios (Stated Policies Scenario, Sustainable Development Scenario, Net-zero by 2050 Scenario), the demand for minerals for clean technologies will increase significantly by 2040, up to six times in the most ambitious scenario (Net-zero by 2050 script). For electric vehicles and battery storage, in the three scenarios a mineral requirement is estimated between 4 and 21.5 million tonnes, compared to 0.4 million tonnes in 2020. According to the Sustainable Development Scenario, by 2040, demand for lithium will be the highest, more than 40 times, followed by graphite, cobalt and nickel, about 20-25 times (IEA, 2021).

Until 2030, lithium reserves are sufficient to meet battery demand, but high-grade deposits are mainly limited to Argentina, Australia, Chile, and China (McKinsey, 2023). There are a number of factors that can affect mineral supply and price volatility: high geographical concentration of production, long project development periods, declining resource quality or environmental issues. For example, the production of some critical minerals is highly concentrated geographically. For lithium, cobalt and rare earths, the world's top three producing countries control more than three-quarters of global production. The Democratic Republic of Congo and China were responsible for about 70% and 60% respectively of global cobalt and rare earth production in 2019. In terms of processing operations, China has a strong presence across the board, refining about 35% of nickel, 60 -65% of lithium and cobalt and almost 90% of rare earths (IEA, 2021).

4.2. The cost of lithium-ion batteries

Over the past decade, the price of lithium-ion batteries has dropped significantly (Figure 5). In 2022, the volume-weighted average price for lithium-ion batteries (including those used in stationary energy storage projects) was $151/kWh in real terms. This price was 7% higher than in 2021 due to the increase in the prices of raw materials and components. For electric vehicles, the battery price was $138/kWh, of which the average cell price was only $115/kWh. This indicates that, on average, cells account for 83% of the total package price. Regionally, the lowest battery prices were in China at $127/kWh (BloombergNEF, 2022).

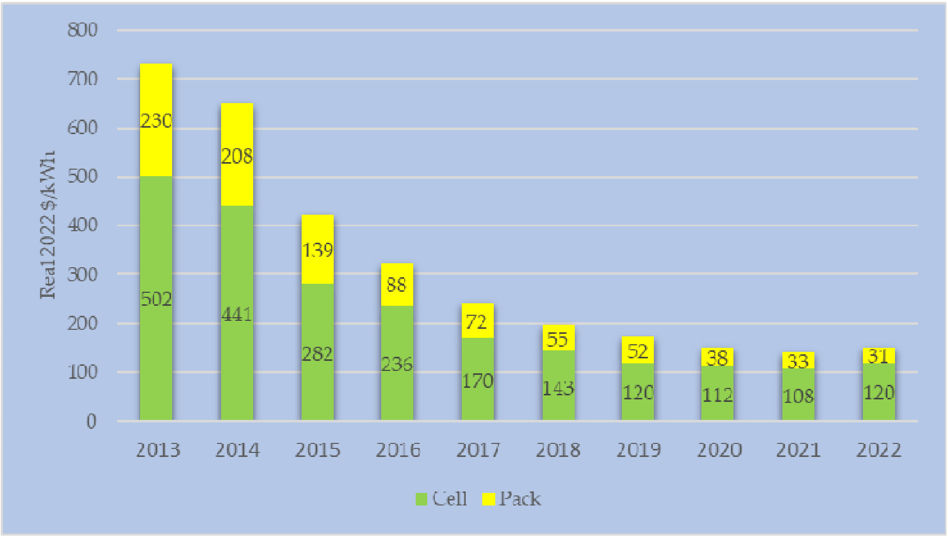

Figure 5. Volume-weighted average lithium-ion battery pack and cell price split (*Source:* BloombergNEF, 2022)

According to Thunder Said Energy (2023), for a typical lithium-ion battery, materials accounted for 10% of a battery's cost in 2012, 50% in 2019, and up to two-thirds in 2022. Thus, it may be difficult to continue the pace of decline of the past decade without saving on materials or changing battery chemistry by reducing or eliminating the use of nickel, manganese and cobalt. In 2022, the price of nickel increased, reaching twice the 2015-2020 average. Also, the price of lithium carbonate has risen steadily over the past two years. At the beginning of 2023, the lithium price was six times higher than the 2015-2020 average (IEA, 2023b). Going forward, the cost of lithium-ion batteries will also depend on continued investment in research and development, manufacturing process improvement and battery recycling.

4.2. Battery recycling

Recycling lithium-ion batteries can contribute to the future sustainability of the transportation system. The recycling industry is just beginning, as most batteries produced by 2023 are still in use. Efficient battery recycling will face some challenges because batteries differ greatly in chemistry and construction, and the cells are often held together with strong glues that make them difficult to disassemble.

In general, recycling is based on two processes, known as pyrometallurgy and hydrometallurgy, which mainly involve the extraction of cathodic materials. The most common is pyrometallurgy, where the cell is first mechanically crushed and then burned, resulting in a charred mass of plastic, metals and glues. Several methods can then be used to extract the metals, including subsequent combustion. Hydrometallurgy, on the other hand, involves immersing battery materials in pools of acid. Sometimes the two methods are combined. Both processes produce certain amounts of waste and emit greenhouse gases (Science, 2021).

Work is currently underway to develop battery recycling processes that minimize their impact. Researchers at Chalmers University of Technology in Sweden, cited by EV Engineering (2023), presented an efficient way to recycle metals from used lithium-ion batteries of electric vehicles, which enables the recovery of 98% of the batteries' lithium. In addition, the loss of valuable raw materials such as nickel, cobalt and manganese is minimized and no expensive or harmful chemicals are required in the process, as oxalic acid (an acid of organic nature) is used.

In recent years, lithium-ion battery recycling plants have multiplied at a rapid pace. As of November 2022, approximately 44 companies in Canada and the United States and 47 companies in Europe were recycling lithium-ion batteries or planned to do so. In addition, automobile companies and battery recyclers have partnered to provide the auto industry with a source of battery materials (USGS, 2023). States also introduce regulations in this regard. In 2018, China imposed new rules aimed at promoting the reuse of electric vehicle battery components.

4.3. Effects on the environment

The production process of lithium-ion batteries has various negative effects on the environment (Majeau-Bettez et al., 2011, Ellingsen et al., 2014, Dunn et al., 2015, Kim et al., 2016, Dai et al., 2019) . The mining and processing of raw materials used in the production of lithium-ion batteries can have significant environmental implications, contributing to climate change, air and water pollution, as well as deforestation, habitat destruction and land degradation. The mining process of lithium requires a lot of water. More than half of the lithium reserves are located in the territory of the states of Argentina, Bolivia and Chile, a region with a very dry climate. In addition to lithium, batteries contain metals such as cobalt, nickel and manganese, which are toxic and can contaminate water sources and ecosystems around mines.

Lithium-ion batteries can only be used for a certain period of time, after which they must be replaced. If landfilled, batteries are a threat to the environment because they can release toxins, including heavy metals, that can leach into the soil and groundwater. One study found that 98.3% of lithium-ion batteries end up in landfills, increasing the risk of landfill fires (Anna Boyden, 2016). Between 2013 and 2020, 245 fires were reported in 28 US states caused by, or likely caused by, lithium-ion batteries in the waste management process. These fires affected the facilities and surrounding communities in a variety of ways, including injuries, service disruptions, and financial losses. Some fires were large and destructive, such as those that destroyed entire facilities and caused extensive property damage and injured firefighters (EPA, 2021).

4.4. Carbon dioxide emissions

All components of a lithium-ion battery are part of a supply chain that begins with the mining and extraction of materials, then continues with the conversion and refining of materials, and finally the production of battery chemicals, cells and packs. All these processes are energy-intensive and have a certain climate impact, depending on the energy source used. Research that analyzed the impact of lithium-ion batteries on the climate showed an impact between 39 kg CO_2 equivalent/kWh and 196 kg CO_2 equivalent/kWh (Cerdas et al., 2018).

About 40% of the battery's carbon footprint, i.e. about 28.5 kg CO_2 equivalent/kWh, comes from the extraction, conversion and refining stage of the cells' active materials, where lithium, nickel, manganese and cobalt are processed into cathode powder. The actual cell production represents about 20% of the carbon footprint, i.e. 14 kg CO_2 equivalent/kWh. About 17.0% of the carbon footprint is attributed to the aluminum content of the battery (Dai et al., 2019, Melin, 2019).

One of the reasons for the large carbon footprint of lithium-ion battery manufacturing is the energy source used during the manufacturing process. In China, the largest producer of batteries, more than 60% of electricity comes from burning coal. Even so, the total lifetime greenhouse gas emissions of electric vehicles are around half that of internal combustion engine cars, on average, with the potential for a further 25% reduction with emissions-free electricity low carbon. For a medium-sized electric vehicle (with a 40kWh battery) lifetime greenhouse gas emissions are around 19.7-21 tonnes CO_2 equivalent, of which 11.7 tonnes from electricity consumption, 5.4 tonnes from vehicle manufacturing and 2.6-4 tonnes from battery production (IEA, 2021).

Comparative data on life-cycle greenhouse gas emissions have also been published by the International Council on Clean Transportation (2021). They show that battery electric vehicles have by far the lowest life-cycle greenhouse gas emissions. Thus, the emissions of a medium-sized electric vehicle are lower than those of a comparable gasoline vehicle by 66%-69% in Europe, 60%-68% in the United States, 37%-45% in China, and 19%-34% in India depending on the electricity mix used.

Conclusions

In the context of climate change, which produces serious effects on the environment and human society, urgent measures are needed to reduce greenhouse gas emissions, including from the transport sector. Electric vehicles represent an alternative to vehicles that use fossil fuels, because the climate impact is significantly reduced.

Implementing cleaner production techniques, promoting recycling and supporting more environmentally sustainable practices throughout the supply chain are essential steps to mitigating social and environmental impacts. Research and development must continue at a sustained pace to reduce the relatively high cost of lithium-ion batteries, extend their lifespan, and use fewer critical minerals such as cobalt or nickel. Identifying alternative solutions for critical minerals through technological innovation can play a major role in improving supply and reducing costs.

As the transition to e-mobility requires increased investment in mineral supply to support the rapid pace of demand growth, actions are needed to encourage new mining projects, provide clear policy signals in the direction of e-mobility and raise awareness of the public about the ecological role of this type of mobility.

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