What are the need for resources of electric cars production, is it sustainable and how?

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WHAT ARE THE NEEDS FOR RESOURCES OF ELECTRIC CARS PRODUCTION, IS IT SUSTAINABLE AND HOW?

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List of abbreviations / Glossary

BEVs = Battery Electric Vehicles

Co = Cobalt

CO2 = Carbon diOxide

EV = Electric Vehicle

GHG = Greenhouse Gas

HEV = Hybrid Electric Vehicle

ICEVs = Internal Combustion Engines Vehicles

IEA = International Energy Agency

Kg = kilograms

kW = kiloWatt

kWh = kiloWatt hours

LFP = Lithium Iron Phosphate

Li-ion= Lithium-ion

LIBs = Lithium-Ion Batteries

LMO = Lithium Manganese Oxide

LTO = Lithium Titanate

MJ = MegaJoules

Na-ion = sodium-ion

NiMH = Nickel-Metal Hydride

NCA = Lithium nickel cobalt aluminum

NMC = Lithium nickel manganese cobalt oxide

PHEVs = Plug-in Hybrids Electric Vehicles

R&D = Research & Development

SDS = Sustainable Development Scenario

SIBs = Sodium-Ion Batteries

US$ = United States dollars

V = Volts

1 Introduction

1.1 Context

Humanity is facing one of its most important challenges. This challenge corresponds to the global warming of earth and its consequences. The most notorious public responsible for this global warming is known: GHG (Greenhouse Gas) emissions. The main responsible for those emissions are humans' activities (Ritchie & Roser, 2020). Various economic sectors are involved in those emissions: 16.2% of GHG emissions in 2016 were coming from transportation. 11.9% of global GHG emissions come from road transport. (See appendix, II. Global greenhouse gas emissions by sector).

There is a necessity to reduce those 11.9% as fast as possible. Those 11.9% GHG emissions come from the burning of fossil fuels in the vehicles on roads (Ritchie & Roser, 2020). Thus, the world must transition out of vehicles using fossil fuels to reduce those 11.9%. As governments are going to ban the sale of fossil fuel vehicles within the next decade in multiple countries, the main solution discussed nowadays is to replace those by their electrical equivalent. Those electrical vehicles are today at the center of the global attention. Besides the concerns about costs, driving range and the lack of charging points, one common issue resides in people asking themselves: Are electric vehicles less pollutants? What about the scarcity of components? What about recycling of the parts?

An investigation was conducted about electric vehicles production considering those questions. There was also in this thesis a gathering of all the details of methodology, analysis, and results.

1.2 Managerial & scientific interests

To begin with, this challenge is interesting from a scientific point of view. The technology evolution of the last decade in electric vehicles domain is massive. Moreover, rapid reduction of GHG emissions is of public interest. The rapid & efficient transition to those electric vehicles is part of the solution. In the transportation sector, the aim is to reduce emissions by 80% at least by 2050 (International Council on Clean Transportation Europe & Georg Bieker, 2021). If this objective is not reached, the goal of the Paris Agreement will not be achieved.

Therefore, the primary mean used to replace fuel cars consist in transitioning to electric ones. « Only battery electric and hydrogen fuel cell electric vehicles have the potential to achieve the magnitude of lifecycle GHG emissions reductions needed to meet Paris Agreement goals. » (International Council on Clean Transportation Europe & Georg Bieker, 2021, p. 3). Main reason is their reduced greenhouse gas emissions if considering whole lifecycle (see appendix, I. Lifecycle GHG emissions of average medium-size gasoline internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030.). Thus, the main global interest in electric cars consists in their potential to fight climate change. However, part of resources needed for batteries are rare. For example, lithium reserves are for now insufficient to produce those batteries from now to 2050 (Weil & al., 2018). This makes clear that the scarcity of components is one of the main challenges faced by electric cars technologies.

Important general interest growth in those vehicles was explained in previous paragraph. But the foreseen high demand in electric vehicles is also attracting managerial interest. Numerous companies understood it. Those are going to offer a broader electric vehicles fleet between 2020 and 2040. Part of them even plan to stop producing fossil fuels powered cars (Weil & al., 2018). And naturally this overall increase in demand will result in an increase in the production of electric vehicles.

Future predicted increases vary between 35% and 54% (between 2016-2017 and 2040) (Pereirinha & al., 2018). Through market forces, companies will develop their activities in that sector. However, this major opportunity brings its challenges. As explained, part of raw materials could be insufficient. Companies will have to invest in R&D to find solutions. Furthermore, this sector has multiple diverse needs (Pereirinha & al., 2018):

- Need to have qualified professionals for production,
- Increasing need in batteries recycling,
- Need in increasing batteries lifetime.

Indeed, while this new kind of vehicles is interesting for companies to conquer new markets, they must face the aforementioned challenges.

1.3 Purpose of the thesis

The main goal of this thesis is an assessment of the availability and sustainability of materials used for electric cars production. As explained, this assessment is critical for future mobility. Road transport need to be electrified massively. Thus, sufficiency of raw materials must be assessed. There are already plenty of raw materials deposits. However, are they enough to face the possibly huge increase in the demand coming over the next years? What solutions could be implemented to reduce raw materials dependency? To assess this goal, the present thesis is divided into 3 main questions:

1) What is the material needed for 1kWh of battery?

2) Is the strong evolution of the demand for electric cars sustainable in terms of resources?

3) What impact could recycling have on this demand for resources?

Those questions are going to be the foundation of this thesis. This foundation will firstly be analyzed in the "Literature review" section. Then, the questions are going to be developed in the "Empirical part" section with additional questions.

1.4 Contribution

The intent of this thesis is to bring a new analysis over the future of electric cars in the society. This analysis will scrutinize evolution of technologies, markets & people in the next years. Therefore, this thesis is not going to be a closed analysis. It has the purpose to bring a new perspective on this industry by:

- Highlighting various aspects of the problem.
- Analyzing potential evolutions.
- Investigating solutions for the sector of electric vehicles production.

This thesis will assess simultaneously present & future problems. Primary objective is to analyze the electric cars' viability with challenging scenarios. This study is not only intended for academic scholars and researchers. It is also aimed at persons in the industry, or people having an interest in this subject in general. Indeed, as explained, the sector of electric vehicles production is of a particular importance. The future society is depending on it. Thus, analyses over this topic should be of general interest. For a topic as important, common mistakes & interrogations should be erased promptly.

1.5 Approach

To answer the main interrogations in scope of this thesis, this document is divided into five main sections, section two starting next.

The approach followed is first to redefine the main topics of interest and objectives, then to introduce and analyze the most recent findings on these topics, and finally to exploit the results of the analysis to achieve the determined objectives.

Therefore, in section two, a literature review will be realized. The first purpose is to have a resume of the actual knowledge about electric cars' batteries. This is going to give additional information useful for this paper. Then the 3 main questions previously presented are going to be analyzed. First, materials needed for batteries & their quantities are going to be defined. That information corresponds to the foundations needed for the next questions. Afterwards, an evaluation of possible demands evolutions for electric cars will be realized. This is going to lead the thesis to sustainability (sub-)questions over:

- Available rare materials resources.
- Technology possibilities.
- Demand's predictions.

Next, the recycling's impact will be evaluated. Assessments are going to be made over its impact on supply chains. The possible evolutions of recycling are also going to be assessed. The consideration will be oriented on solving resources & production excesses. An assessment over research materials used is going to be accomplished.

Finally, a resume of the answers to the sub questions will be available, there will also be connections between the different findings and a conclusion about the answers from papers to the main research questions.

In section three, the empirical part will consist in data collection, treatment & forecasts. In this section, further sub questions will be solved. Those questions will be solved in 2 parts:

1) Methodology part. There, data sources will be presented, and the computations made to treat those data & make forecasting will be explained.

2) Result part. There, results of the computations will be presented & analyzed.

This section's objective is to assess the answers from papers in literature review. Real data & predictions will be used as foundations of this section.

In section four, an interpretation of the results & hypothesis will be developed. The objective is to demonstrate the limitations of this thesis. The existing theory is going to be extended. This will highlight whether the results confirm the literature review content or not and, when the empirical part does not confirm the literature review content, alternative explanations will be given.

The conclusion in section five will contain a resume of this thesis' findings. Assessments over the solutions proposed are going to be developed. An analysis of this thesis contributions will be accomplished. Contributions given by this work are divided between the managerial and scientific ones. The thesis' limits will also be emphasized and, furthermore, certain leads to improve the research on this area will be mentioned.

2 Literature review

2.1 Actual knowledge about batteries in electric cars

2.1.1 Reminder of what is meant by batteries in electric cars

This thesis is about battery in electric vehicles. To speak about those, it is logical to start with a basic definition of battery. A battery cell is composed of three crucial elements: an anode, a cathode, and an electrolyte (see appendix, III. Schematic representation of the (a) discharging and (b) charging process of a metal-based secondary battery.). Such a battery cell does not exceed a voltage of 5V (5 volts). Since more than 5 volts are needed for most applications, a battery is composed of several battery cells connected in series (Muench & al., 2016). There is a definition for a battery: « The term battery usually describes a ready-to-use product, providing the required voltage, current, shell, and seals. » (Muench & al., 2016, section 3.1). Therefore, a battery is:

- Composed of multiple cells.
- Protected with a shell and seals.
- Providing the required voltage.

Now that the notion of batteries has been defined, it must be included in the context of electric cars. « EV (electric vehicles) batteries are quite different from those used in consumer electronic devices such as laptops and cell phones. They must manage high power (up to a hundred kW) and high energy capacity (up to tens of kWh) within a limited space and weight and at an affordable price. » (Young & al., 2012, section 2.1). In simple terms, EV batteries are a large kind of batteries. However, EV and HEV (Hybrid EV) use two precise kinds of batteries: NiMH (nickel-metal hydride) and Li-ion (lithium-ion) batteries (Young & al., 2012). In 2012, most HEV used NiMH batteries because it was the most mature technology (Young & al., 2012). Nevertheless, in 2020, Li-ion batteries were quoted as « the dominant technology for Evs » (Xu & al., 2020, paragraph 3). As they represent the current dominant technology, this thesis is going to be focused on LIBs (lithium-ion batteries).

2.1.2 Explanation of actual knowledge

Today, numerous studies explain that LIB (lithium-ion battery) is the dominant kind of battery system used in EVs. LIB is acknowledged as the leading technology for electric transportation energy storage sector (Zeng & al., 2019). In fact, batteries in electric vehicles exist since 1860, and were first lead-acid batteries. Those lead-acid batteries were then replaced by Nickel-Metal Hydride Batteries. Those batteries have a higher efficiency in electric vehicles (Sun & al., 2019). Nowadays, lithium-ion batteries are the most used energy storage systems in the market. They have various advantages compared to previous technologies (Manzetti & Mariasiu, 2015):

- High power storage capacity.
- Small size.
- Lightweight.

There are also other advantages described as specific energy, energy density, and cycle (see appendix, IV. Comparison of the characteristics of various power batteries.).

Indeed, lithium-ion is nowadays the first battery type used in electric vehicles industry. However, there is not only one type of lithium-ion battery. There are six main types of lithium-ion batteries currently used for different applications (Hannan & al., 2018). Between those six main types, one is not suited for electric vehicles' applications: lithium cobalt oxide. This battery uses a large amount of Cobalt. The lack of cobalt's accessibility makes it too costly (Hannan & al., 2018). This battery type is used in a limited number of EVs, as in the Tesla Roadster (Miao et al., 2019). However, this option is going to be discarded because of its limited application in EVs market. Therefore, analyses will be expanded on 5 types of lithium-ion batteries. Those 5 types are the most used in electric vehicles' industry (Zeng & al., 2019):

- Lithium manganese oxide ($LiMn_2O_4$)-(LMO).
- Lithium iron phosphate ($LiFePO_4$)-(LFP).
- Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$)-(NMC).
- Lithium nickel cobalt aluminum ($LiNiCoAlO_2$)-(NCA).
- Lithium Titanate ($Li_4Ti_5O_{12}$)-(LTO).

Those five types of batteries represent the full market share of lithium-ion batteries in EVs. Each type of battery has its advantages & defaults compared to the others. For example: « LMO and LFP batteries may generally be considered the least environmentally critical, since they do not contain particularly toxic or rare metals. » (Raugei & Winfield, 2019, p. 927). Also, NMC, NCA & LTO present excessive costs of materials & complex manufacturing. This results in higher battery's costs. However, NMC & NCA batteries have a higher energy density than LMO and LFP batteries. NMC & NCA batteries also present a longer lifespan than LMO batteries (Liu et al., 2018). Furthermore, there is not always one type of battery by vehicle: « Sometimes LMO battery and NMC battery are combined to power an EV in order to enhance the performance and also decreases the battery cost. » (Liu et al., 2018, p. 208). About LTO, those represent the favorite batteries for buses applications. This is due to specificities of LTO batteries (high safety, long life, and fast charge).

Even though EVs are not at their maturity level, they have already advantages compared to their ICEVs (Internal Combustion Engines Vehicles) counterparts:

The cost by mile is about 2 cents for EVs versus 12 cents for ICEV. Furthermore, energy usage to is more efficient in EVs. ICEVs use only 21.5% of their fuel energy to move the vehicles while EVs use about 77%. The residual percentage of energy corresponds to waste. « It suggests that EVs are about 3.6 times more efficient than ICEVs » (Farfan-Cabrera, 2019, p. 473). EVs have also benefits on the environmental side. Indeed, they present no direct GHG emissions at allwhen running. However, EVs have still some disadvantages regarding classic ICEVs (Christidis & Focas, 2019):

- Higher prices.
- Several manufacturing materials are considered as rare.
- Infrastructure development (such as electric charging stations) is not sufficient in numerous European countries.

Thus, this technology must aim to higher development. This development will serve to reduce the prices along with improving materials' usage. Infrastructures also need to be more expanded.

2.2 Material needed for 1 kWh of battery

2.2.1 Types of batteries & corresponding materials

In the previous chapter, the five main types of batteries used in EV's s were introduced. Going further, to have a complete view of the materials' needs for batteries, those must be evaluated. According to the research of Liu et al. (2018) and Zeng & al. (2019): LMO, LFP, NMC, NCA & LTO are the 5 types of batteries that represent the current and the near future market of EVs' batteries.

However, one of those batteries has different compositions. Indeed, the NMC battery may have multiple cathode compositions. Those compositions contain different proportions of nickel, manganese & cobalt (Porzio & Scown, 2021). Those compositions have evolved because of the need to reduce the amount of cobalt used. Indeed, cobalt presents a high price volatility & a limited resource availability. NMC-811 ($LiNi0.8Mn0.1Co0.1O2$) has the least cobalt concentration of all cathode compositions. Thus, interest for NMC-811 is steadily growing (Wood et al., 2020). NMC-811 is seen as one of the most promising technologies in the coming years. However, NMC-111 & NMC-622 are the most currently commercialized batteries (Tang et al., 2021) (among NMC types). More precisely, NMC-111 are intensively used in EVs, while NMC-622 were recently introduced. Those two kinds of batteries have a major disadvantage: compared to NCA batteries, they use high cobalt's quantities. However, as explained, the NMC-811 batteries currently in development use less cobalt. This battery type possesses the ability to compete with NCA on this level. This kind of NMC battery is expected to be in use in the middle 2020s (Jetin, 2020). (For information: NMC-622 composition: 60% nickel, 20% manganese & 20% cobalt).

According to the research of Porzio and Scown (2021), the common lithium ion batteries chemistries are:

- NMC–Graphite.
- NCA–Graphite.
- LFP–Graphite.
- LFP–LTO.
- LMO–Graphite.

The objective here after was to find the varied materials' quantity needed in EVs batteries. The following tables contain interesting information about batteries' composition. In the first table, there is the repartition of materials in mass percentage. In the second table, the amount of material per kWh is presented. Both tables give an overview of the proportionality of materials among battery types:

Element	NMC-111 [% mass]	NMC-532 [% mass]	NMC-622 [% mass]	NMC-811 [% mass]	NCA [% mass]	LFP [% mass]	LMO [% mass]
Li	0.078	0.022	0.077	0.077	0.072	0.044	0.038
Ni	0.197	0.083	0.354	0.471	0.489	–	–
Mn	0.184	0.466	0.111	0.055	–	–	0.608
Co	0.198	0.334	0.119	0.059	0.092	–	–
Al	–	–	–	–	0.014	–	–
Fe	–	–	–	–	–	0.354	–
P	–	–	–	–	–	0.196	–
O	0.343	0.095	0.339	0.338	0.333	0.406	0.354

Table 1-Element mass ratio per cathode active material (Porzio & Scown, 2021).

Material	Cell component	NMC-111	NMC-532	NMC-622	NMC-811	NCA	LFP	LMO
Cathode active material [g kWh⁻¹]	Cathode	1757.45	1288.79	1481.48	1257.53	1358.70	2031.28	2341.74
Graphite [g kWh⁻¹]	Anode	858.02	863.13	840.45	841.18	857.71	956.61	793.59
Carbon black [g kWh⁻¹]	Cathode additive	36.61	26.85	30.86	26.20	28.31	42.32	48.79
PVFD [g kWh⁻¹]	Cathode binder	36.61	26.85	30.86	26.20	28.31	42.32	48.79
	Anode binder	17.51	17.61	17.15	17.17	17.50	19.52	16.20
Aluminum [g kWh⁻¹]	Cathode current collector	104.32	77.24	88.18	75.08	79.12	156.85	149.66
	Positive terminal assembly	29.57	27.28	27.06	25.75	27.05	35.88	32.08
	Cell container	57.55	50.93	51.93	48.85	51.48	73.53	66.51
	Module heat conductors	103.34	90.39	93.27	87.34	91.67	133.48	121.61
	Module enclosure	69.03	64.43	64.03	61.14	63.57	82.09	74.86
Copper [g kWh⁻¹]	Anode current collector	244.18	182.03	206.82	176.73	186.31	364.82	347.55
	Negative terminal assembly	98.13	90.52	89.81	85.46	89.75	119.06	106.47
	Cell interconnection	29.45	27.17	27.01	25.65	26.85	35.77	31.98
LiPF6 [g kWh⁻¹]	Electrolyte salt	2.79	2.37	2.52	2.31	2.40	3.75	3.42
Ethylene Carbonate [g kWh⁻¹]	Electrolyte fluid	221.14	188.14	199.40	183.43	190.14	297.29	270.79
Dimethyl Carbonate [g kWh⁻¹]	Electrolyte fluid	179.26	152.51	161.63	148.69	154.13	240.98	219.50
Polypropylene [g kWh⁻¹]	Separator	16.80	12.40	14.18	12.07	12.73	25.33	24.19
	Cell container	8.83	7.81	7.96	7.49	7.89	11.28	10.20
Polyethylene [g kWh⁻¹]	Separator	16.80	12.40	14.18	12.07	12.73	25.33	24.19
Polyethylene Terephthalate [g kWh⁻¹]	Cell container	3.83	3.39	3.46	3.25	3.43	4.90	4.43
Misc electronics [g kWh⁻¹]	BMS	11.08	11.32	10.28	10.26	11.05	11.81	10.34
Total [kg kWh⁻¹]		3.90	3.22	3.46	3.13	3.30	4.71	4.75

Table 2- Module material inventory per kWh for a module with a 10 kWh energy capacity (Porzio & Scown, 2021).

The critical materials needed for EVs are represented in both tables. The second table provides more precisions about cathode active material & other components. With this table, the amount of material necessary for the LMO, LFP, NMC & NCA batteries is known. However, one of main battery's types is not included: the LTO battery.

LTO battery is a specific battery's type. When LMO, LFP, NMC & NCA batteries are mentioned, it is usually their cathode composition which is discussed. Their anode is always composed of graphite (natural or artificial). An LTO battery is a modified lithium-ion battery. It uses lithium-titanium instead of graphite on the surface of its anode. This gives the anode a bigger surface area allowing electrons to enter and leave the anode quickly (Schröer et al., 2020). Currently, LTO is used with LFP, forming what was called before LFP-LTO batteries. It must be noted that, LTO batteries aforementioned are in fact LFP-LTO batteries. So, LTO & LFP-LTO refer to the same chemistry, they can be considered as the same term.

According to the research of Helbig et al. (2018), in LFP-LTO batteries, four main differences with other battery's types are present:

- The graphite anode is replaced by lithium-titanium based anode.
- Copper is absent of LFP-LTO batteries.
- Titanium is used in this kind of battery only.
- There is more lithium contained in LFP-LTO batteries.

One of primary objectives of this thesis consists in an availability & risk assessment of rare raw materials. Titanium is considered to be the second least at-risk raw material in BEVs supply chain. However, lithium is at high risk and « it accounts for 6.5% of the mass in LFP-LTO » (Helbig et al., 2018, p. 281). Furthermore, LFP-LTO batteries are two times less energy dense than their LFP-graphite counterparts (Peters & Weil, 2016). Other main resources at high supply risks (cobalt, copper & graphite) are not contained in LFP-LTO batteries.

Finally, most of research over this subject highlight the 4 other types of battery: LMO, LFP, NMC & NCA. In a few papers, LTO are considered to represent a non-negligible part of future EVs' market (Liu et al., 2018). However, in a couple of other papers, they do not appear (Weil et al., 2018). This technology is currently in development. Trying to make more hypothesis on a non-finished technology is going to be done later in this thesis. However, this part on batteries' chemistry is different. Since this part will serve as foundation for next chapters, taking a technology at an unclear development stage should be avoided. For the following of this thesis, the LTO technology will therefore be omitted.

2.2.2 Critical locations of the materials needed

As explained before, numerous different metals are present in battery technologies of EVs. However, a couple of those metals can be considered of highest importance. This, because of two factors: Their resources are limited and not abundant (compared to their predicted use) & those metals are mostly produced in a couple of countries. Thus, this results in a narrow market, and a narrow market can be at risk for development of EVs.

The materials mentioned as at risk are (National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019):

- lithium,
- natural graphite,
- nickel,
- manganese,
- cobalt

Those materials are present in the following figure. There, the quantities of material reserves along their countries are represented:

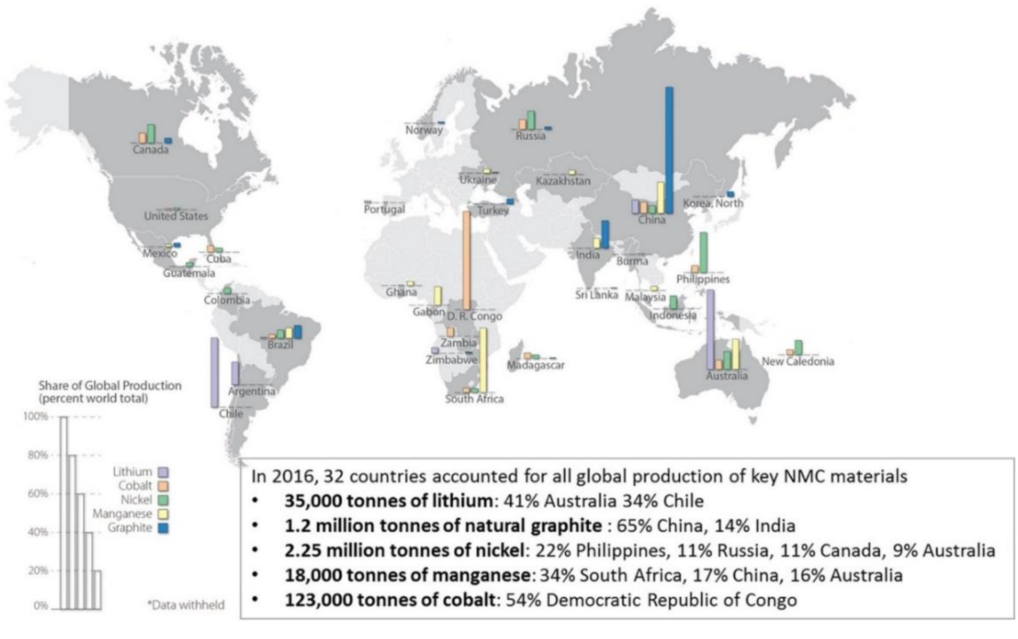


Figure 1-World mining industry production for materials used in LIB in 2016 (Mayyas et al., 2019).

For the lithium, 91% of its production is concentrated in Australia, Chile & Argentina. 59% of cobalt is produced in Democratic Republic of Congo. Graphite is produced at 67% in China. Manganese is produced at 63% in South Africa, China & Australia. There is only nickel in this list that can be considered as less concentrated. Another crucial point regarding metals supply risk is their refinery location. Indeed, those metals must be refined before being assembled in batteries. Two of the most critical materials of LIBs, lithium & cobalt, are refined in massive quantities by China (see appendix, V. Refinery capacity and production of cobalt & VI. Lithium carbonate production.).

Indeed, China is highly involved in the raw materials extraction & refinement for EVs. China also represents a high part of those materials' demand. This has one advantage: China's companies desire to assure future material availability for their own sake.

However, as explained, a narrow market can be at risk for EVs' development. A market contained in only a couple of countries reduces safety of the supply chain & transparency of the market (National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019).

2.3 Strong evolution of demand for electric cars & sustainability

2.3.1 Global outlook of actual & possible future evolutions

Now, that main battery types along with their critical raw materials have been described, this thesis' focus in this section will be on the global impact of that technology. According to the report of the International Energy Agency (2020), the strong evolution of electric cars in the global market has already begun. Between 2014 & 2019, the market of EVs has expanded at an average rate of 60% by year. The total of 7.2 million electric vehicles in 2019, is already qualified as a huge increase.

For the potential future evolutions, there are multiple scenarios possible. In the report of the International Energy Agency (2020), two scenarios are mentioned:

1) The stated policies scenario. in this scenario, the existing government policies stay as planned. The total number of electric vehicles accounts for 7% of all vehicles in 2030. This results in nearly 140 million EVs in 2030. As explained, there were 7.2 million electric vehicles in 2019. This results in an increase of 132.8 million EVs between 2019 & 2030.

2) The sustainable development scenario. This scenario follows the Paris Agreement's needs. The objective is a 30% market share reach for electric vehicles (not including two-wheels vehicles). This results in 245 million electric vehicles in 2030. The resulting increase is strongly higher than in stated policies scenario. This scenario would need an additional 237,8 million new electric vehicles between 2019 & 2030.

The first scenario is frequently used in other papers about the EVs' market evolution. According to the research of Berckmans et al. (2017), there would be a 7.6% market share for EVs in 2030. a different result is present in another scenario which considers more technology development. the EV's market share could be of approximately 10% in Europe and more than 20% in the United States (Heitel et al., 2020)

Considering global growing importance of electric vehicles, an interesting question is: Is it possible for the most ambitious transition from ICEVs to EVs to happen? And at what cost? One of the most ambitious scenarios possible consists in reducing vehicles' CO2 emissions to near zero by 2050. Even if it is ambitious, this scenario is considered necessary to limit the increase of the global temperature between 1.5 and 2°C. (International Council on Clean Transportation et al., 2021). Another scenario that follows the actual trend of the European Union foresees 70% of car share to be electric in 2050 (Krause et al., 2020).

Thus, the scenario of near zero emissions by 2050 will be considered as the most interesting. It would be a challenge because of extensive material needs. However, it would be the most efficient in the fight against climate change. Thus, this scenario is going to be investigated in the empirical part of this thesis.

2.3.2 Reserves of critical materials & supply risks

According to the research of Habib et al. (2020), 4 metal's types could be the most affected by a high increase in EVs' demand: Cobalt, lithium, nickel & dysprosium. In worst-case scenario, this study highlights a global cobalt shortage by 2035. While global reserves of lithium and nickel drop at their lowest level around 2050. One solution proposed to avoid this is having a better mix in the battery types. In this research (Habib et al., 2020), additional usage of LMO batteries along NCA batteries is mentioned. Parallel solutions are:

- Decreasing the number of necessary batteries in the EVs.
- Improving the recycling.

The dysprosium does not present this potential shortage problem. (See appendix, VII. Annual demand and the resulting amount of geological reserves of different metals considered in this study for the baseline, moderate and stringent scenarios.). Dysprosium is a rare metal; thus, it is considered as at risk. However, when investing probable depletion caused by EVs' increasing demand, dysprosium is no longer considered at risk. Therefore, additional investigations will be accomplished on the cobalt, lithium, and nickel metals. Their higher global supply risk regarding EVs is important. Potential reserves depletion must also be investigated.

Lithium is a metal that is not particularly rare. Furthermore, it is distributed globally. There are two main source types for Lithium: silicate minerals available in mineral mines & mineral-rich brines. Mineral-rich brines constitutes the cheapest option to collect lithium. Given that, most of the lithium produced today is sourced from those brines. However, the strong increase in demand results in a steadily more significant part produced from minerals. Lithium is not considered at risk regarding possible reserves depletion. Even in worst case scenarios, the lithium reserves are sufficient to support demand (Habib et al., 2020 ; Kavanagh et al., 2018). Nevertheless, an important supply risk remains. The reason behind is a possible lack of lithium's production regarding demand. According to the research of Swain (2017), there are two solutions:

1) Strong improvement of the recycling of lithium-ion batteries with high recovery rates for lithium.
2) Finding of alternatives in lithium recovery from low-grade primary and secondary resources (Swain, 2017).

Cobalt is at considerable risk because of its possible shortage around 2035 (Habib et al., 2020). According to the research of Fu et al. (2020, p. 2990): « However, our lower and upper bounds on Co demand in 2030 are 160 and 280% of world refinery capacity in 2016, respectively… The IEA reports Co EV demand of 350 tonne/yr for an EV30@30 Scenario, which reaches 30% market share for EVs by 2030 (EV sales reach 43 million). This demand, combined with other sources of demand (even using our low estimate of those sources), would exceed even our upper bound on supply (470 tonnes demand vs 458 tonnes supply) ». Indeed, scenario with the biggest transformation from ICEVs to EVs supports that hypothesis. Even a scenario with highest production of cobalt is not going to be sufficient. However, this scenario considers actual battery mix of EVs along actual means of production. Whereas battery mix is evolving continuously. Also, there are new means to extract cobalt being investigated (Fu et al., 2020).

Even if nickel is also a rare metal, it could consist in a partial solution to the cobalt's problem. EVs' batteries rely steadily more on nickel than on cobalt. This brings opportunities to reduce cobalt supply risk for two reasons (Nguyen et al., 2021):

1) The most nickel is used in the batteries, the least cobalt is needed

2) Cobalt is also a by-product of nickel. Increasing nickel's production increase cobalt's production.

So, nickel could also represent an opportunity to reduce the cobalt supply risk. According to the research of Olafsdottir and Sverdrup (2021), nickel global depletion should happen after 2150. Indeed, there are enormous quantities of nickel stocked in deposits worldwide. Therefore, nickel depletion problem is not a short-term problem. However, nickel is also a material at risk regarding future production-demand equilibrium. Demand is expected to exceed supply for nickel by 2037 if nothing changes (Turcheniuk et al., 2018). This risk should not be underestimated and represents a challenge. Especially if there is an increase of nickel's production to replace cobalt.

2.3.3 Actual costs & predictions

Since the past 20 years, the battery costs for EVs have undoubtedly fallen. They went from 1000 US$ per kWh in 2008 to an estimated average cost of 300 US$ per kWh in 2014. Furthermore, the future projections also predict costs reductions. It is incredibly important that costs reductions continue their course. Indeed, elevated costs of EVs remain a barrier for consumers. (Edelenbosch et al., 2018).

However, actual battery technologies consume considerable quantities of rare & expensive raw materials. Raw materials prohibitive costs could block the cost reduction. « The improved model predicts nickel-manganese-cobalt (NMC) battery prices will fall only to about $124/kWh by 2030 – much cheaper than today, but still too expensive to truly compete with ICEVs, due primarily to the high prices of cobalt, nickel, and lithium. » (Hsieh et al., 2019, p. 218). This highlights the importance of developing EVs' technologies for price reduction. Technologies must be improved to lower to the minimum EVs' costs. The lowest the costs are going to be, the most consumers will buy EVs.

2.3.4 Energy required to produce & recycle batteries

In this section, EV's energy requirements & emissions are going be investigated. The purpose of this chapter is not to contradict the established fact that EVs are greener. This thesis already quoted various academic papers explaining the ecological interest of EVs. However, EVs' production uses resources and energy of various kinds. Those resources & energy will be investigated in this chapter. Firstly, emissions due to LIBs battery production will be assessed.

Indeed, EVs can reduce energy use and environmental impacts compared to ICEV. However, the production of lithium-ion batteries may cost a considerable amount of energy. Furthermore, certain battery chemistries may be non-environmentally friendly. Battery with chemistry NMC-111 is one example. For 1 kWh of this battery, production takes 1,126 MJ (Megajoules) of energy. Furthermore, it emits 72.9kg of CO2 (Carbon Dioxide) in its cradle-to-gate process (see appendix, IX. Cradle-to-gate impact breakdowns and bill of materials (BOM) of 1 kWh NMC111 battery. Blue denotes material inputs; orange denotes energy inputs for cell production.). The production of battery materials represents a large part of this pollution (Dai et al., 2019). However, this battery chemistry is among the most pollutants. It needs to be compared with the other main batteries' chemistries seen previously.

In figure below, data over CO2 production of battery chemistries are available. The chemistry used in this figure for NMC battery type is the NMC-622. It explains why this battery has the lowest CO2 emissions by kWh:

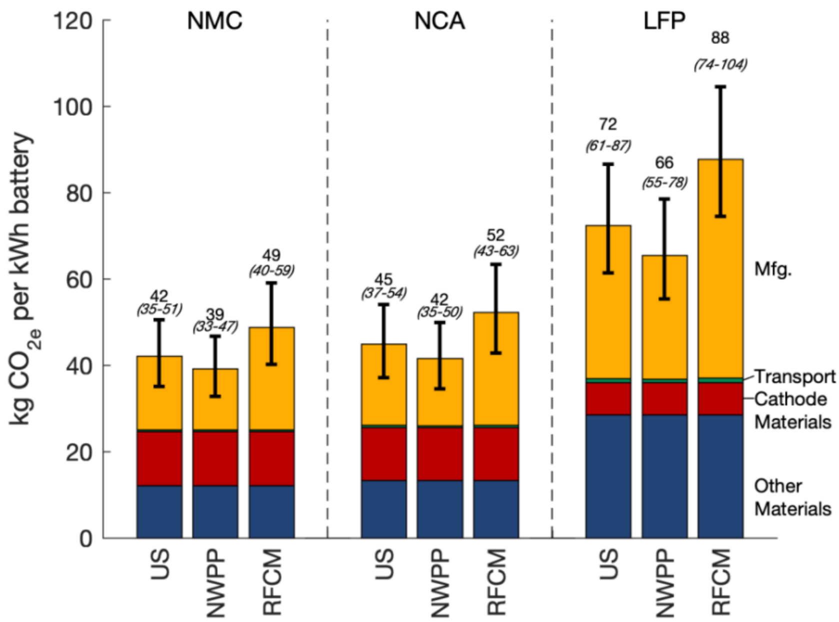


Figure 2-Median and 95% confidence interval of kg CO2e per kWh of battery emitted while manufacturing NMC, NCA, and LFP cylindrical cells with US average, NWPP, and RFCM grid emissions (Ciez & Whitacre, 2019).

About NMC batteries, one chemistry more currently used is the NMC-622. This chemistry is going to be investigated along NCA and LFP batteries. According to the research of Ciez and Whitacre (2019), NMC-622 batteries emit significantly less CO2 emissions than their NMC-111 counterparts. Indeed, one NMC-622 battery production emits between 39 & 49 kg of CO2 per kWh. Producing one NCA battery emit between 42 & 52 kg of CO2 per kWh. Production of one LFP battery emits the most, between 66 & 88 kg of CO2 per kWh. The lower emission rate of NMC- 622 constitutes an additional reason to replace NMC-111 chemistry. Reduction of rare materials needed is the first reason behind this chemistry replacement. Regarding energy consumption, NMC-622 batteries use considerably less energy (in MJ) than NMC-111. It takes between 520 & 620 MJ to produce a kWh of the NMC-622 battery. For NCA & LFP batteries, they respectively use between 550 & 660 and between 860 & 1090 MJ/kWh. Per kWh of battery produced, the LFP batteries uses the most energy. Those energy consumptions are available in the below table:

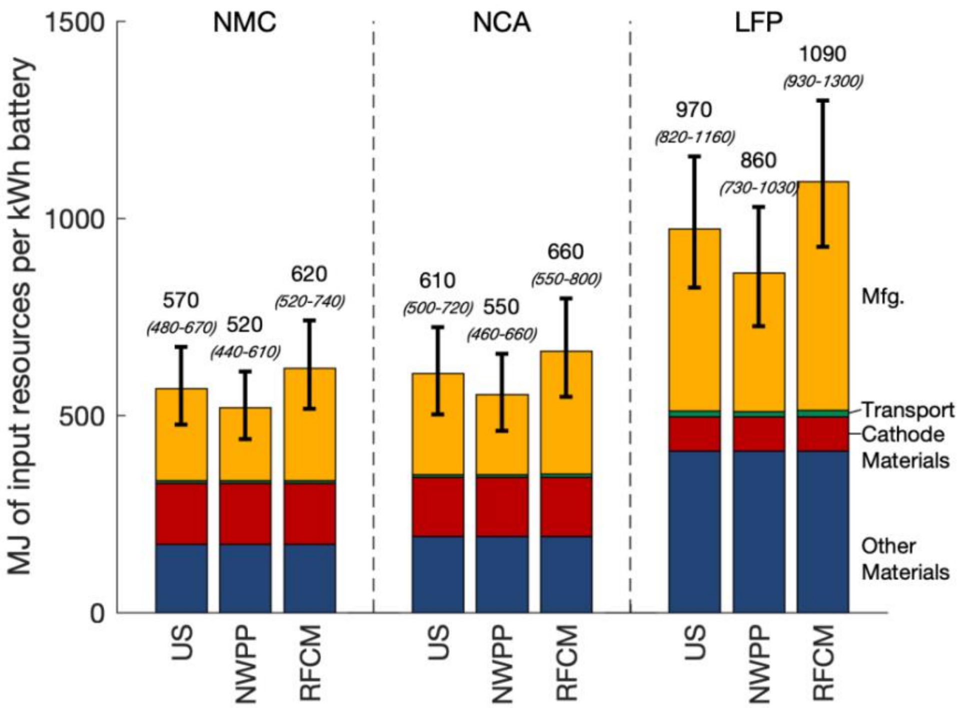


Figure 3-Median and 95% confidence interval of MJ of energy consumed per kWh of battery while manufacturing NMC, NCA, and LFP cylindrical cells with US average, NWPP, and RFCM grid emissions (Ciez & Whitacre, 2019).

An important question coming from those results should be the following: Could recycling be useful in reducing CO2 emissions & energy consumption? Recycling is useful to reduce the use of raw materials. However, it is less useful in reduction of CO2 emissions & energy usage. Nevertheless, reasonable savings of CO2 emissions & energy usage are possible for NMC & NCA batteries. In that case, the LFP batteries emit even more CO2 if recycled & it uses more energy (See appendix, X. (a) Median and 95% confidence interval for CO2e emissions per kWh of battery for battery manufacturing and recycling. (b) median and 95% confidence interval of the net CO2e emissions avoided using difference recycling processes. & XII. (a) Median and 95% confidence interval for MJ of embodied energy per kWh of battery for battery manufacturing and recycling. (b) median and 95% confidence interval of the net MJ embodied avoided using difference recycling processes.).

2.4 Impact of recycling on the industry

As explained, metals with highest supply risks for EVs' batteries production are cobalt, lithium, and nickel. Thus, the following chapter is going to be focused on the recovery possibilities of those materials.

Over lithium recycling, two outcomes are possible depending on the recycling technology level:

- Recycled lithium could not reach necessary quality level to be re-used in batteries. It could thus be used in basic demand sectors (glass, glass-ceramics, alloy, …).
- Recycled lithium could reach necessary quality to be re-used in batteries. In that case, batteries are for EVs & non-EVs sectors applications.

If the lithium recycled is of low quality, the saving of the primary resources would be limited. It will result in mining increase to get quality lithium. This would also lead to costs increase. Furthermore, a considerable part of lithium reserves is located in high-risk countries. if lithium's demand grows too sharply, it would lead to bigger supply risks problems. That could be strongly problematic for the industry. The recovery of lithium nowadays in Europe is not efficient. Therefore, it is of particular importance to develop new recycling solutions for lithium. Mitigation of lithium supply risks depend on this development (Ziemann et al., 2018). Nowadays, only 3% of LIBs are recycled in the world. Although, it is estimated that recycling could save up to 13% of LIBs cost per kWh.

However, Cobalt and nickel are already recovered when those batteries end up in recycling (Mossali et al., 2020).

Efficient recycling techniques to recover lithium and cobalt from used batteries already exist. Depending on the leaching agent, they have recovery rates between 80 and 100% (see appendix, VIII. Recovery rates of Li and Co from spent LIBs.).

According to the research of Chan et al. (2021), there is a realizable technique more efficient to recover Lithium, cobalt, nickel & manganese. With precise chemicals and conditions, this technique has approximately a 100% recovery rate. Thus, technical knowledge necessary to recover most of rare metals in spent EVs' batteries already exists. The LIBs recycling infrastructures are not, for the time being, globally in place. Cobalt is already recycled in contrary to lithium only for economic gains (Or et al., 2020).

When replacing fossil-fueled cars with EVs, the problem of GHG emissions is reduced. However, batteries consume rare metals that come primarily from a couple of countries. This is an additional supply problem that ICEVs cars do not present. Furthermore, once used, EVs batteries need to be disposed of. The purpose of this transition consists not in replacing a problem with others. Thus, as the recovery of spent batteries is technically feasible, it also is a necessity (Gaines, 2019).

2.5 Possible substitutes & complements for actual batteries

As explained before, there are 5 main types of batteries currently used in EVs: LMO, LFP, NMC, NCA & LTO. LTO battery type could be important in the future. It may represent more than 5% of lithium-ion batteries in the market in 2025 (Liu et al., 2018). However, this kind of battery is mostly interesting to replace graphite. And as LTO battery still need a cathode, which is one of the 4 main battery chemistry types, this technology will be avoided for the following of this thesis.

There are new batteries technology developed that could be promising for the future of the market. For example, sodium-ion (Na-ion) battery (SIB) has promising characteristics (Abraham, 2020). This kind of battery presents the main advantage to be produced with cheap and abundant materials. It also works as well as certain lithium-ion batteries (Abraham, 2020). However, it is still in development for EVs because of performance & capacity problems. This battery technology is being steadily more developed. It is quoted as « one of the most promising next-generation battery technologies beyond LIB. » (Zhang et al., 2019, p. 30). However, as those batteries have already good characteristics for stationary storage usage (Chayambuka et al., 2020), SIBs (sodium-ion batteries) are going to be considered for that application.

An interesting technology already known since multiple years is hydrogen fuel cell technology. Hydrogen fuel cells function by burning dihydrogen gas they stock. Nowadays, it is used in niche markets, such as for forklifts, taxi fleets, or buses (Bethoux, 2020). Hydrogen fuel cells for EVs have advantages and disadvantages compared to lithium-ion batteries:

- As advantages: Hydrogen fuel cells combined in a car allow those to have high driving range with low operating costs. Those cells also present fast recharging capacities and are highly safe.
- As disadvantages: Useful electric power in hydrogen fuel cells is proved to be less efficient, about 50% (and in LIBs it is about 90%). Hydrogen fuel cells are also still expensive and not compact.

Hydrogen fuel cells have also been investigated to be used as an extender in LIBs EVs. This combination creates the possibility to have the advantages linked to both technologies.

According to the research of Wu et al. (2019), this opportunity could present numerous advantages:

- It could increase the range of BEVs by more than 50% for small ones and 25% for bigger ones.
- It could decrease the charging infrastructure dependency of BEVs.
- It could decrease the need for bigger lithium-ion batteries. Resulting in rare raw material savings.
- It would also reduce the costs of BEVs with higher ranges.
- Control unit in hydrogen fuel cells extender could help controlling its temperature. This controlling would increase the lifetime of lithium-ion batteries.

Another range extender investigated is zinc-air battery pack. It has also the advantage to increase the ranges of lithium-ion batteries (Tran et al., 2020). This also leads to the following advantages: It results in lower costs for the battery packs. Also, it leads to less dependency on charging infrastructure and to a lower utilization of rare materials for the design of EVs (by battery size decrease).

2.6 Resume, conclusion & research questions

Numerous researchers have investigated the future role of batteries in the transportation system. Most assessments were made on batteries' materials potential problems (Christidis & Focas, 2019 ; Mayyas et al., 2019 ; National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019) …. Research have also been conducted on different battery types usable in EVs (Hannan & al., 2018 ; Raugei & Winfield, 2019; Zeng & al., 2019) …. Papers over advantages & disadvantages of those batteries and on the transition feasibility from ICEVs to EVs were also realized (Habib et al., 2020 ; International Energy Agency, 2020) …

One battery type dominates EVs' market: it is lithium-ion battery (Zeng & al., 2019). This is the most essential information to begin with. For EVs, the five main types of lithium-ion battery are LMO, LFP, NMC, NCA & LTO (Liu et al., 2018 ; Zeng & al., 2019)). LTO batteries were still in development in 2018, so they nowadays represent a negligible market share. Also, several papers simply ignore LTO batteries (Weil et al., 2018). It is why the four other types are going to be more investigated. Those four battery types have distinct characteristics & chemistries. However, those batteries have common components crucial for the EVs' industry.

Within those materials, most at risk are lithium, nickel & cobalt for 2 reasons (Habib et al., 2020 ; National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019):

- There are highly concentrated in certain geographical areas.
- Those materials could be in shortage in a few years.

Cobalt is the material with highest supply chain risks. It could be in a state of global shortage (worst case scenario) by 2035. Lithium & nickel could be at their lowest around 2050. Furthermore, those rare materials could constrain recent price reductions of EVs (Hsieh et al., 2019).

Those rare materials can be recycled with excellent recovery rate (about 100%) using specific techniques (Chan et al., 2021)). Recycling is a solution to reduce the use of raw materials and to avoid the use of landfill. Therefore, the recovery by recycling of used batteries is a valuable tool (Gaines, 2019). However, recycling is less useful to reduce CO2 emissions & energy use by batteries' production. There is a small saving for most battery types. However, with LFP battery type, recycling even uses more energy & emits more CO2 (Ciez & Whitacre, 2019).

Another solution to reduce raw materials issue are in substitutes & complements technologies. Sodium-ion batteries, hydrogen fuel cells & zinc air battery pack as extender are three promising technologies. Sodium-ion batteries could replace part of lithium-ion batteries in the future. SIBs do not meet LIBs performance nowadays. Thus, their use to replace LIBs in EVs remains hypothetical. However, they work as well as LIBs for stationary applications (Chayambuka et al., 2020). Furthermore, SIBs are produced from cheaper and more abundant materials (Abraham, 2020).

Hydrogen fuel cells & zinc air battery pack could serve as a battery extension. Hydrogen fuel cells have numerous advantages as (Bethoux, 2020):

- Low operating costs.
- Fast recharging capacity.
- High safety.
- Decrease the charging infrastructure dependency for EVs.
- Allow economies of scarce materials.

However, hydrogen fuel cells are still expensive & not compact. Zinc-air extender also have the advantages to lower costs of battery packs, lower rare materials use & increase the autonomy (Tran et al., 2020).

The purpose of this thesis is to answer the following main research question:

« What are the needs for resources of electric cars production, is it sustainable and how? »

In this thesis, the objective is to answer to that question in the most global way possible. The transition to electric cars is a worldwide challenge. Therefore, the empirical part is going to evolve in that mindset.

Thanks to the literature review, main concepts of batteries in EVs have been discussed. Their composition and the main challenges linked to the supply chain have been pointed out. With this information available, there remains questions which needs a more in-depth analysis:

1) Considering only batteries in already commercialized EVs, is the most ambitious scenario aforementioned (245 million of electrical vehicles in 2030) possible?
2) What impact could recycling have to prevent production & scarcity problems with EVs?
3) What impact could complements have on the industry and the scarcity of the resources? Which would be the most interesting?
4) What is the impact of those different solutions together? What impact does it create for the sustainable scenario of the IEA of 2050?

In the empirical part, the sustainable scenario of the IEA will be named "sustainable development scenario". SDS (sustainable development scenario) is going to be its abbreviation.

Those sub questions are the basis to assess the future of EVs market. Also, they will highlight necessary technologies to be used. Whether it is in production, recycling, complement technologies, ... A comparison between the empirical answers & literature review will be done. The idea being that this empirical part is to analyze databases & make predictions. Those predictions will rely on hypotheses. Predictions' goals are to obtain a frame to assess the efficiency of aforementioned technologies. This frame is not guaranteed to be close to future reality. However, it tries to stay as close as possible of results found in reliable papers.

3 Empirical part of the thesis by main subject

This section starts with a presentation and explanation of the methodology used to conduct this empirical study and the reasons for its implementation. It includes an explanation about the choice of the data as well as the way in which they were handled. Then, the results of those data manipulations are demonstrated.

The purpose here is to construct a reflection with real life data to obtain the tools needed to answer the thesis questions & sub-questions.

3.1 Presentation of the methodology and choice of data

3.1.1 Methodology and choice of data for the first sub question

To begin with, the first question: « **Considering only batteries in already commercialized EVs, is the most ambitious scenario aforementioned (245 million of electrical vehicles in 2030) possible?** » was tackled. Here, the data needed to support the analysis were:

- Materials availability
- Demand for EVs' production
- Remaining demand
- Predicted recycling rates

For that purpose, data from various research were considered (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Xu et al., 2020 ; Valero et al., 2018).

Thanks to the data provided in these research, it was possible to make computations about predicted demand of EVs for 2030. This has been done as follows:

- First, there was a merging of the materials' needs of EVs along with their predicted production (Xu et al., 2020).
- Then, a comparison was made with the materials reserves available. These data have been aligned with the rare materials' demand share that the EVs should represent in the future (Nguyen et al., 2021).
- After that, the predicted recycling rates for the battery market & the global market of rare materials were applied (Statista, 2021a ; Valero et al., 2018). Those rates were applied to an average of materials in battery market & a predicted number of EVs' battery disposed (Publications Office of the European Union, 2018). Along that, the predicted market share of EVs' battery was considered (Statista, 2021a). This data merge was done to see the following: "What would be the impact of EVs' production on rare materials?"

It is important to note that the computation was made under four strong assumptions:

1) Only the production of EVs was considered.
2) Predicted recycling rates evolve without extra efforts.
3) The technology does not evolve regarding complements & substitutes of classic LIBs batteries.
4) The battery's chemistries investigated are already in use, potential future chemistries are not considered.

The results were then compared with forecasts of materials' demand shares (comparison between EVs' demand share & the rest of the demand).

Finally, they were compared to other previsions about materials reserves forecasts. Note that there is no recycling analysis on copper because of the meaningless impact of EVs over its reserves.

3.1.2 Methodology for second sub question

Regarding the second question: “**What impact could increased recycling have to prevent production & scarcity problems with EVs?** “, three sources were investigated to determine proper answers.

Those sources contain:

- Data regarding quantities of materials by battery together with share of critical material used in EVs (Statista, 2021a).
- Recycling rates predicted for those materials (Valero et al., 2018).
- Average lifetime of batteries along the amount of used EVs’ batteries over time (Publications Office of the European Union, 2018).

Those data, along with results from the first research question were merged. They were then used to assess the impact of a strong hypothesis: The possibility to have recycling rates for critical materials increased to 100% by 2030.

A linear growth rate was determined to have a logical increase of recycling rates. The method was to take the already known rate, & make it grow from 2022 to 2030 with this objective of 100% recycling. With 100% recycling of materials, most efficient techniques give a rate of 98% for lithium & 100% for cobalt (see appendix, VIII. Recovery rates of Li and Co from spent LIBs.). For nickel, according to the research of Tayar et al. (2020), the best rate is at 95%.

Then, an assessment over different reserves depletions scenarios was made. The scenario with the predicted recycling rates was used along the 100% objective for 2030. The purpose of those computations was to assess the different impacts over the depletion of the different scenarios.

3.1.3 Methodology for the third sub question

To be able to answer the sub question: “**What impact could possible complements have on the industry and the scarcity of the resources? Which would be the most interesting?**”, multiple technologies are going to be investigated:

- Sodium-ion (Na-ion) battery as replacement of LIBs (lithium-ion batteries) for stationary applications.
- Hydrogen fuel cell as complement of LIBs to reduce their size.
- Zinc-air extender complements of LIBs as well.

First, sodium-ion (Na-ion) batteries have been investigated. This kind of battery has the main advantage to be produced with cheap and abundant materials while working as well as some Lithium-ion batteries (Abraham, 2020 ; Zhang et al., 2019). In fact, according to the research of (Chayambuka et al., 2020), they should be considered for the replacement of LIBs in stationary applications. Using the data over forecasted share of stationary applications in the battery market, an hypothesis of growing replacement of LIBs by SIBs (sodium-ion batteries) was investigated, with its impact on the production of LIBs & the depletion of resources.

A second possible complement resides in using hydrogen fuel cells as extension of lithium-ion batteries. They could be used to reduce the need for the biggest battery packs in EVs, resulting in less rare materials used (Wu et al., 2019). This possibility was investigated, along with the zinc-air battery pack extender, which has the same advantages (Tran et al., 2020). Three hypotheses were made to assess the possible impact of those extenders:

- 25% demand for large & medium EVs reduction by 2030 thanks to extender
- 50% demand for large & medium EVs reduction by 2030 thanks to extender
- 75% demand for large & medium EVs reduction by 2030 thanks to extender

Those scenarios involve that the market share reduction of large & medium EVs results in an equivalent market share increase in small EVs.

3.1.4 Methodology for fourth sub question

Regarding the question: "**What is the impact of those different solutions together? What impact does it create for the sustainable scenario of the IEA of 2050?**", research & aggregation of previous computations were made.

To begin with, the most ambitious scenario of EVs' transition was taken. According to the research of Habib et al. (2020), in 2050, this scenario provides us with the number of 1.6 billion cars. To make predictions, the baseline used were the data from the research of Nguyen et al. (2021). Then, using forecasting tool from excel, predicted results with lower & upper bounds were calculated (see appendix, XVIII. Forecasted EVs evolution between 2040 & 2050, table & chart.). The total of upper bound forecasted by the software was the closest result to this 1.6 billion EVs ambitious scenario. Since the objective of this thesis is to evaluate most ambitious scenarios possibility for electric transition, these upper bound predictions were used for further computations.

This forecast was also used to assess the share of Plug-in hybrid vehicles compared to full electrics, for further computations (see appendix, XIX. Forecasted PHEVs market share evolution between 2040 & 2050, table & chart.).

Another forecast was needed also for recycling for the market share of materials in EV market (see appendix, XX. Forecasted market share evolution between 2038 & 2050 of critical materials.)

After that, computations from the first research question were extended to have the SDS developed until 2050. This considers the predicted evolution of recycling rates. It assesses the sustainability of the critical materials if:

- There is no use of new battery technologies
- There are no extra efforts in recycling
- There is no development of complementary solutions

Then, further computations were realized to assess impacts of the hypothesis of higher recycling investment, usage of complements & substitutes. According to the research of Gross et al. (2018), it takes a median of 18 years for an innovation to be commercially widespread. Considering this duration, and a hypothesis of an increase in growing recycling rates, three hypotheses were investigated. Those hypotheses take as a starting point year 2020:

1) Low development: Increase of 1.5 factor of recycling growth rate compared to its initial growing rate. 18 years after, 20% market reach for Sodium-ion batteries in stationary storage applications, then the constant growth continue until 2050. 10% decrease in motor size predicted thanks to extenders applications after 18 years, then the decrease continues at constant rate.
2) Medium development: Increase of 2.0 factor of recycling growth rate compared to its initial growing rate. 18 years after, 40% market reach for Sodium-ion batteries in stationary storage applications. 20% decrease in motor size predicted thanks to extenders applications after 18 years, then the decrease continues at constant rate.

3) High development: Increase of 3.0 factor of recycling growth rate compared to its initial growing rate. 18 years after, 60% market reach for Sodium-ion batteries in stationary storage applications. 30% decrease in motor size predicted thanks to extenders applications after 18 years, then the decrease continues at constant rate.

3.2 Presentation of the results

In this section, results of the different data manipulations are going to be presented. The structure is going to be based on the research questions. The purpose consists in developing a reflective answer with real life data.

3.2.1 Results for the first sub question

As a reminder, the following question was investigated: "**Considering only batteries in already commercialized EVs, is the most ambitious scenario aforementioned (245 million of electrical vehicles in 2030) possible?**" as explained in the methodology presentation part.

In this first sub question, the possible scarcity of rare materials was investigated. The objective was to see if the reserves of rare materials used for batteries were sufficient to have 245 million EVs worldwide by 2030.

With more than 7 million (7,545,790) EVs already on road in 2019 (Xu et al., 2020), the remaining 237 million (237,454,210) would need:

- 14% of known reserve of lithium (more than 2 million tons)
- 37% of known reserve of cobalt (more than 2 million tons)
- 2% of known reserve of copper (more than 20 million tons)
- 14% of known reserve of nickel (more than 11 million tons)

In the appendix (XII. Lithium, Cobalt, Copper & Nickel reserve evolution caused by EVs production under predicted recycling assumption), there are graphics available that highlight the evolution of the reserve.

With the numbers & the graphics, it is noticeable that EVs have a high potential of depletion regarding cobalt. With predicted recycling rates, 37% of the cobalt reserve would be depleted to the 237 million electric fleet vehicles. It highlights that particularly for this resource, the need of recycling for rare materials is important. However, Copper will not be investigated further. 2% reserve of copper would be used in this scenario. Moreover, this rate was computed without considering recycling. In literature review, copper was not quoted as "at risk". Thus, no further computations are going to be made over copper.

Lithium & nickel positioned themselves at second place, 14% of the reserve depleted by EVs' production in 2030 remains a huge amount. With a comparison of the EVs' demand share for those rare materials, it is noticeable that the reserves usage due to EVs production follow the same trend as the demand share of those (see appendix, VII. Annual demand and the resulting amount of geological reserves of different metals considered in this study for the baseline, moderate and stringent scenarios.).

Thus, with predicted recycling rates, there could be an enormous decrease of those rare materials by 2030. However, the most ambitious scenario of EVs' production until 2030 remains possible, even with actual models & predicted recycling rates. Looking at less ambitious scenarios (see appendix, VII. Annual demand and the resulting amount of geological reserves of different metals considered in this study for the baseline, moderate and stringent scenarios.) rare materials do not deplete. The more moderate scenarios are thus feasible without constraints.

Finally, an analysis over predicted amounts of rare materials recycled compared to the materials' needs of those for EVs was conducted. The graphical representations are visible in appendix (XIV. Share of predicted rare materials recycling compared with EVs production.).

First observation is: this predicted recycling could have a noticeable effect on cobalt & nickel production, however on lithium this effect is not noticeable. The most probable explanation resides in the following evolution of recycling rates, the first table represent the evolution for the global market of those materials, the second for the precise market of batteries.

Mat/year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Co	34%	35%	36%	36%	37%	38%	38%	39%	40%	40%	41%
Li	1,2%	1,3%	1,3%	1,4%	1,4%	1,5%	1,6%	1,6%	1,7%	1,8%	1,9%
Ni	30%	30%	31%	31%	31%	32%	32%	32%	33%	33%	33%

Mat/year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Co	68%	69%	70%	72%	73%	74%	76%	77%	78%	80%	81%
Li	1%	1,0%	1,1%	1,1%	1,2%	1,3%	1,3%	1,4%	1,4%	1,5%	1,6%
Ni	60%	61%	61%	62%	62%	63%	64%	64%	65%	66%	66%

Table 3-Evolution of recycling rates (first table is for materials outside Evs' market. Second is for batteries market) (data sources: (Statista, 2021a ; Valero et al., 2018))

In this table, there is an enormous difference between lithium recycling rates & the recycling rates of Cobalt & Nickel. The forecasted recycling rate of lithium represents such a small amount that it could have no impact on rare materials consumption in EVs production.

A comparison between predicted recycling quantities & predicted production needs' for EVs was conducted.

Demand covered by recycling, predicted rates	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Co	2,193%	1,868%	1,832%	2,246%	2,338%	3,103%	7,916%	11,276%	12,386%	11,944%	11,668%
Li	0,033%	0,031%	0,032%	0,042%	0,047%	0,066%	0,169%	0,242%	0,269%	0,258%	0,247%
Ni	2,036%	1,710%	1,643%	1,964%	1,985%	2,548%	6,405%	8,982%	9,662%	9,217%	8,856%

Table 4-Computations of demand covered by predicted recycling. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

Thus, with actual recycling rates & predicted evolutions, the impact of recycling could be already meaningful to prevent production problems for Nickel & Cobalt. However, regarding Lithium, the produced recycling quantities is too weak compared to the yearly needs.

According to the research of (Habib et al., 2020), the concern over rare materials developed is defensible. Lithium, nickel & cobalt suffer of an enormous decrease of resources between 2015 & 2050 (see appendix, VII. Annual demand and the resulting amount of geological reserves of different metals considered in this study for the baseline, moderate and stringent scenarios.). The primary concern resulting from this analysis resides in cobalt consumption. In this stringent scenario (which is the ambitious scenario, from the IEA), there would be a depletion of cobalt between 2030 & 2035. This could be catastrophic for the electric transition.

3.2.2 Result for second sub question

Regarding the following question, “**What impact could recycling have to prevent production & scarcity problems with EVs?**”, the investigation consisted in creating a hypothesis of rapid recycling increase. The hypothesis used is 100% recycling for all materials for 2030. This high hypothetical rate was used to see possible effects of a high recycling increase on production & reserves.

When investigating this hypothesis, results most connected to reality are represented by cobalt recycling. The change is more perceptible regarding nickel. However, there is a noticeable change over lithium, the recycling rate is strongly distanced from reality. Indeed, even with the technical capabilities of recycling industries, lithium recycling is not a priority. (Economic reason to investigate).

In the following tables, the rate of material demand covered by recycling is indicated. First for the predicted growth rates, then for the 100% recycling in 2030 hypothesis.

Demand covered by recycling, predicted rates	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Co	2,193%	1,868%	1,832%	2,246%	2,338%	3,103%	7,916%	11,276%	12,386%	11,944%	11,668%
Li	0,033%	0,031%	0,032%	0,042%	0,047%	0,066%	0,169%	0,242%	0,269%	0,258%	0,247%
Ni	2,036%	1,710%	1,643%	1,964%	1,985%	2,548%	6,405%	8,982%	9,662%	9,217%	8,856%

Demand covered by recycling, 100% hypothesis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Co	2,180%	1,935%	1,976%	2,526%	2,741%	3,794%	10,097%	15,010%	17,248%	17,305%	17,533%
Li	0,033%	0,046%	0,073%	0,144%	0,239%	0,505%	1,953%	4,217%	7,060%	10,209%	14,788%
Ni	2,002%	1,792%	1,836%	2,343%	2,530%	3,476%	9,354%	14,061%	16,236%	16,629%	17,168%

Table 5-Comparison of demand covered by predicted recycling & demand covered in a 100% recycling rate in 2030 hypothesis. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

Again, the biggest difference is over the lithium, its recycling is predicted to have no impact on demand with predicted recycling rates. The next assessment will investigate the impact of those recycling rates on the known reserves. Those results comparisons are also available in charts (see appendix, XV. Share of rare materials recycling with 100% recycling 2030 hypothesis compared with EVs production.)

The following assessment investigates the impact of those recycling rates on the known reserves. In the following charts, there is the comparison in material depletion in predicted recycling scenarios against the 100% recycling scenario by 2030 :

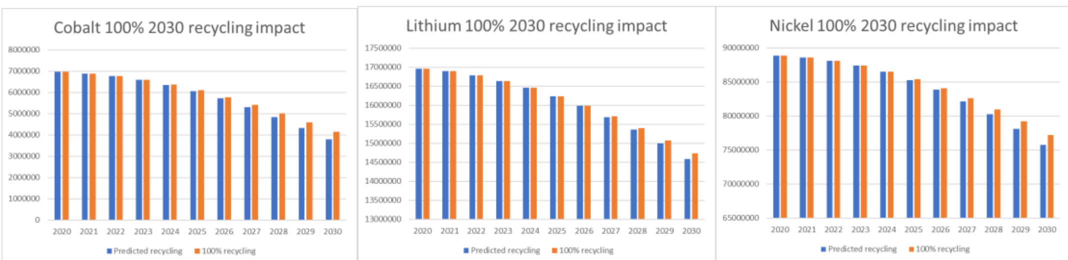


Figure 4-Assessment of 100% recycling impact on reserves depletion. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

The above charts illustrate that there is already a visible change in the depletion of reserves for those materials. Considering that the batteries deplete in an average of 8 years (Publications

Office of the European Union, 2018), the weak difference between the hypothetical 2030's 100% & the predicted rates seem logical. The market for those batteries is supposed to grow at high rate after 2022, which is not a year with an enormous quantity of batteries to recycle 8 years later.

3.2.3 Results for the third sub question.

For third sub questions "**What impact could possible complements have on the industry and the scarcity of the resources? Which would be the most interesting?**", the following technologies were investigated:

- Sodium-ion (Na-ion) battery as replacement of LIBs for stationary applications.
- Hydrogen fuel cell as complement of LIBs to reduce their size.
- Zinc-air extender complements of LIBs as well.

Regarding the hypothesis of attaining 100% of sodium-ion batteries production for stationary storage use in EVs, following results were found.

Total amount of materials needed compared to the savings	2022	2023	2024	2025	2026	2027	2028	2029	2030
Percentage saved of lithium in that hypothesis	0	1,2%	2,2%	2,9%	2,1%	3,5%	4,3%	4,7%	5,8%
Percentage saved of cobalt in that hypothesis	0	0,9%	1,6%	2,2%	1,6%	2,7%	3,3%	3,6%	4,4%
Percentage saved of nickel in that hypothesis	0	0,1%	0,3%	0,4%	0,3%	0,4%	0,5%	0,6%	0,7%

Table 6-Computations of rare materials saving in stationary with 100% SIBs usage hypothesis. (Data sources : (Nguyen et al., 2021 ; Statista, 2021b ; Xu et al., 2020))

Those results were obtained on the hypothesis that SIBs production start in 2023. The production increase is supposed to be constant to reach 100% in 2030. There is an important gain to make over lithium & cobalt in that scenario. However, the effects over total nickel consumption are limited. Comparative graphics is available in the appendix (XVI. Lithium, Cobalt & Nickel saving with 100% SIBs for stationary storage estimation comparison with materials needs.).

Regarding hydrogen & zinc air extenders, Computations were made with the 3 scenarios (25, 50 & 75% of market share reduction thanks to those extenders). Important to note: those size reductions where only applied to BEVs. PHEVs (plug-in hybrids electric vehicles) are particular: bigger PHEVs have smaller batteries (Xu et al., 2020).

To begin with, the following chart represents the average rate of rare material savings possible with the use of hydrogen & zinc air extenders:

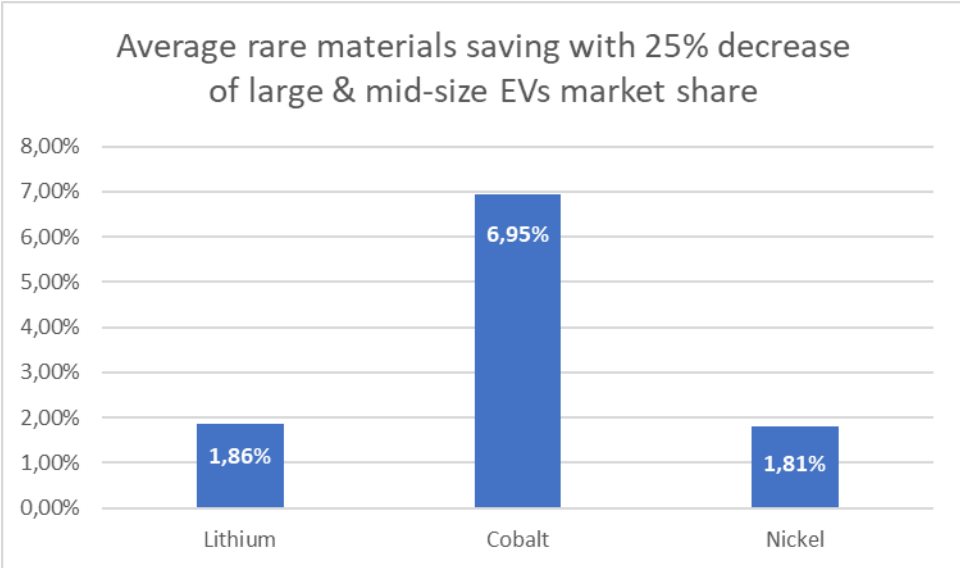


Figure 5-Computation of rare materials saving in 25% decrease hypothesis in Large & mid-size batteries market shares. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

Proportionally, Cobalt represents the highest savings of rare materials thanks to battery size reduction. In terms of gross quantities, Nickel is the metal that could represent the most savings. However, what is of interest here is the proportional saving that could contribute to avoid production shortage & material scarcity.

Graphics containing the reserves remaining amount in 2030 by hypothesis are available in appendix (XVII. Lithium, Cobalt & Nickel remaining reserves by hydrogen & zinc-air extender use impact on large & mid-size EVs market shares.)

3.2.4 Results for fourth sub question

Regarding the research question “**What is the impact of those different solutions together? What impact does it create for the sustainable scenario of the IEA of 2050?**”, different results were determined. First, what amount of known materials' reserves would be used by hypothesis? Results are available in graphics below.

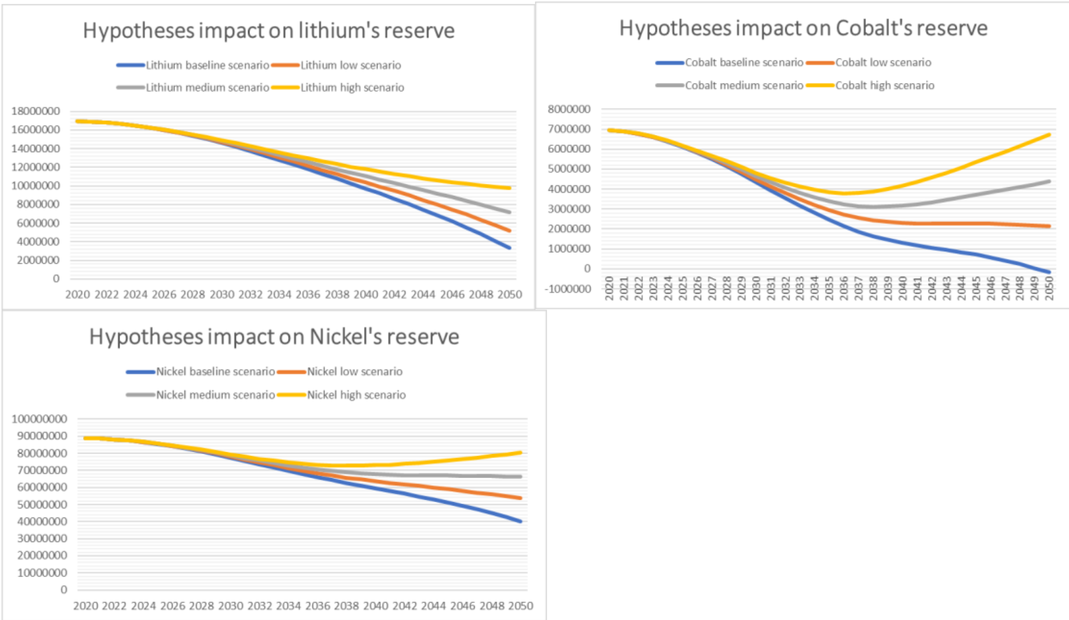


Figure 6-Computation of baseline & 3 hypothesis scenario depletion reserves for 2050. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

There, impacts of higher recycling evolution & extenders use are applied. Sodium-ion batteries, supposed to be intended for stationary storage applications, are considered later. In above charts, recycling & extenders hypotheses represent a significant impact in reserves depletion. Cobalt is the material with the highest depletion risk. This is also the most impacted material by the hypotheses. Therefore, this material should be one of the main focuses for material recycling & consumption reduction.

However, this analysis is focused only on predicted EVs material usage. This material usage share is going to be compared to predicted reserves depletions due to EVs. Graphic below show the materials reserves depletion by hypothesis. This depletion results only from EVs' predicted production. It is compared with predicted market share from EVs for those materials (see appendix, XX. Forecasted market share evolution between 2038 & 2050 of critical materials.):

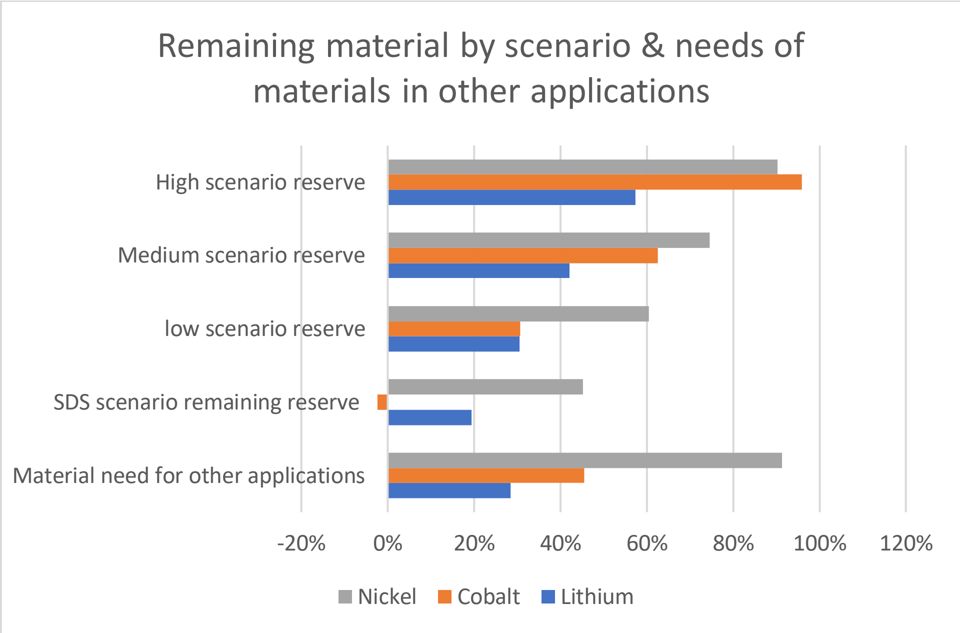


Figure 7-Comparison between computations of baseline, 3 hypothesis scenarios with demand of materials for other applications for 2050. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

This graphic highlights the potential problem of materials depletion. The recycling & extenders solutions represent an important alternative to depletion. If recycling & extenders usage increases, the depletion problem would experience an important reduction. Although the hypotheses are pessimistic: no consideration of new reserves discoveries, no consideration of new chemistries battery usages in EVs, ...

Regarding sodium-ion batteries evolution, an assessment was realized over the stationary applications. Objective consisted in possible market share increase of EVs in rare material depletion. Computations over predicted material needs' evolution in stationary applications made that analysis possible (see appendix XXI. Material usage predicted evolution in stationary.). In the following graphic, increase in EVs' usage of rare materials is represented:

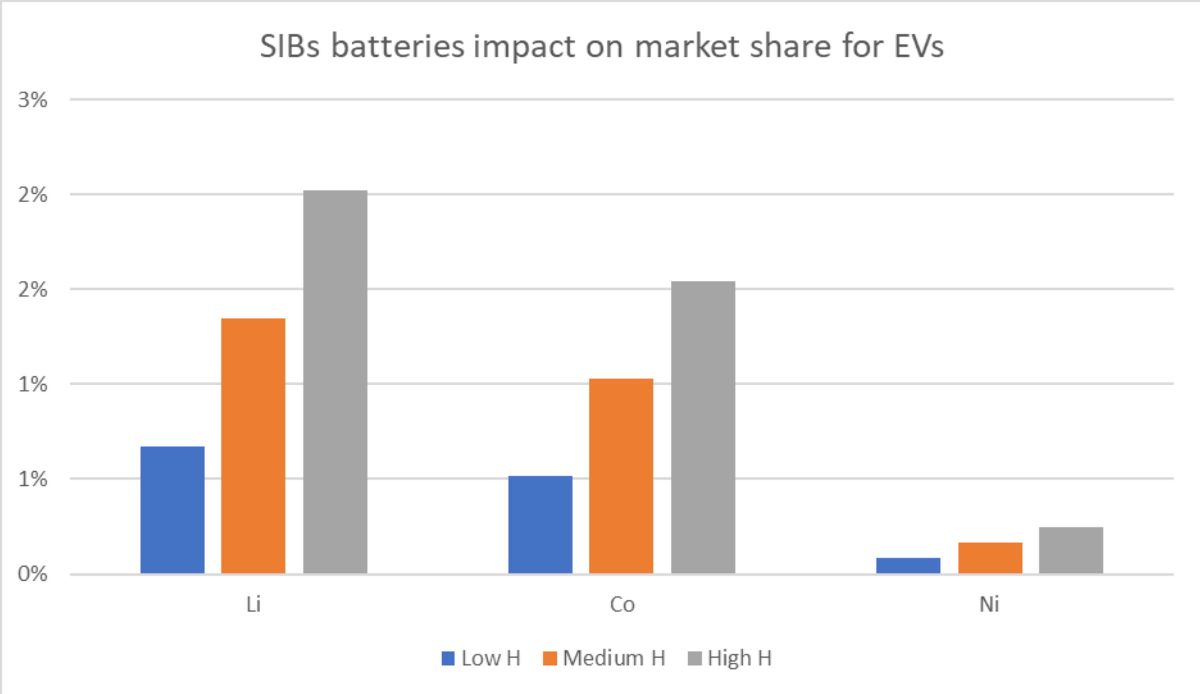


Figure 8-Computations of rare materials saving in stationary in the 3 hypotheses for 2050. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

Sodium-ion batteries applications have thus low possible impact on EVs market share. Maximum increase is of 2% for lithium, which provides low additional flexibility.

4 Discussion

In this section, results analysis & limitations are going to be discussed.

The results highlight the importance of further developments in the industry in the domains of recycling and use of extenders.

For what concerns recycling, the predicted recycling rates evolution (Valero et al., 2018) & battery chemistry (Xu et al., 2020) are not sustainable. The use of materials' reserves (especially Cobalt) in this scenario is excessive. As discussed in the literature review, this scenario would lead to enormous demands of raw materials. This could also create additional dependency with a couple of countries. Also, it increases the risk of facing global production problem.

Recycling those rare materials is a necessity. Recycling techniques to retrieve most of materials contained in batteries already exists. Increasing the recycling is going to reduce the rare materials depletions & demand. Which represent a more sustainable & secured choice regarding supply chain.

Extenders usage also represents a crucial tool. This reduces the need for larger batteries. And this reduction of batteries results in a reduction of the demand for raw materials, which is also more sustainable & secure.

Sodium-ion batteries constitute a sustainable alternative to lithium-ion batteries. The usage of this battery kind was analyzed in stationary storage applications. As explained, it is the domain in which this technology is best suited. This technology is also a good indirect support for EVs market. The less lithium-ion batteries are used outside EVs' applications is the better, as it increases rare materials availability for EVs' production.

This thesis has however its limitations:

First of all, strong hypotheses were used to make the empirical part.

Fixed chemistries for batteries are one of the most impacting. Indeed, there are numerous other chemistries being developed. Part of them is planned to be used in a near future. According to the data from the research of Xu et al. (2020), new batteries with other types of technology could be used very soon. And it is to be noted that those batteries contain no Cobalt, so having considered these technologies in this thesis would have decreased the need for cobalt.

Clearly the hypothesis taken creates a difficulty regarding materials depletion. It is one of the possible hypotheses with the highest rare materials consumption.

Secondly, the predictions made represent a big unknown. Those are compared with scientific papers & results. However, predictions remain vague regarding reality. Those were used to have a representative idea of potential high EVs' production evolution.

Also, extrapolations about part of data were necessary to enable the calculations. Calculations that resulted in yearly results & approximate figures for horizon 2050. Those extrapolations also constitute a potential gap with future reality.

Finally, numerous potential technologies were ignored. Companies are working on green fuel to keep ICEVs running. Hydrogen fuel cells may still be a possible technology in green transportation. Sodium-ion batteries could evolve enough to be used in transportation. In summary, a large number of other technologies were ignored.

Of course, that was a necessity to avoid multiplication of computations, but nevertheless, this could be criticized as a lack of exploration of possibilities.

Overall, this thesis consists in a review of the EVs' industry sustainability. It gives a global overlook on its state. It also highlights potential problems in the most sustainable scenario (International Energy Agency, 2020). It makes clear that the material most at risk because of EVs production is Cobalt, and that increasing the recycling rate & using extenders is the most positive impactful on Cobalt. Lithium & Nickel suffer also of high supply risk, and therefore recycling improvement along with innovative technologies are a necessity.

5 Conclusion

Humanity is facing one of its most important challenges: Climate change. Worldwide, transportation sector is a principal factor of that change. An ambitious vehicle transition from internal combustion to electric is considered as necessary (International Council on Clean Transportation et al., 2021).

The aim of this thesis was to assess the possibility of that change. After the possibility has been assessed, problems were determined. Then, solutions were found & analyzed.

The transition from ICEVs to EVs is possible. However, it must be properly realized. Considering the hypothesis of no new battery chemistries, the previsions of EVs' market are not sustainable. Cobalt reserve would be below 0 in 2050. Lithium & nickel depletion could be enormous. This depletion, considering the whole market, would also be excessive.

Comparison market share/ scenarios reserve remaining in 2050	Material need for other applications	SDS scenario remaining reserve	Lack of reserve for other application
Lithium	28,50%	19,49%	-9,02%
Cobalt	45,46%	-2,41%	-47,87%
Nickel	91,30%	45,23%	-46,07%

Table 7-Computation of baseline scenario for 2050 compared with other applications' materials demand. Lack of reserve is the difference between rates. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

Furthermore, a large demand for those rare materials would present another problem. The materials are mostly concentrated in a few countries which creates an important dependency (National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019). Reducing their yearly demand would reduce that problematic dependency.

Therefore, scientists designed various solutions worldwide to help prevent this problem. Solutions selected in this thesis are:

- Higher recycling rates evolution of critical materials
- Sodium-ion battery as a substitute of LIBs in stationary applications
- Extenders in EVs battery packs to allow a reduction of battery packs' size

From these solutions, three hypotheses were developed. The purpose was to assess possible impacts of the solutions. Among those three solutions, two had direct impacts on the EVs' market: Higher recycling rates & extenders of EVs batteries. Those results are presented in table below (compared with rest of market need):

Comparison market share/ scenarios reserve remaining in 2050	Material need for other applications	low scenario reserve	Medium scenario reserve	High scenario reserve
Lithium	28,50%	30,56%	42,08%	57,38%
Cobalt	45,46%	30,68%	62,54%	95,96%
Nickel	91,30%	60,53%	74,57%	90,30%

Table 8-Computation of baseline & 3 hypotheses scenario for 2050 compared with other applications' materials demand. (Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

Thus, even the lowest hypothesis developed of direct solutions have an important impact. This proves that recycling & extenders could play key roles in sustainable development of EVs.

Regarding Sodium-ion application, this solution also represents a potential part of the solution. Indeed, while its application is not considered in EVs, Sodium-ion batteries could play a key role as stationary storage. And the more this kind of battery is used, the less lithium-ion battery would be needed for stationary storage and therefore be available for EVs.

Despite its assumptions and limitations, this thesis provides important insights. Those solutions are applicable nowadays. This means that EVs industry could be developed in a sustainable manner. Moreover, innovative solutions are going to be developed, possibly more sustainable. Furthermore, there is the possibility that the number of usable deposits increase. Either through discoveries or through new extraction tools.

From a Managerial point of view, by applying today the described solutions (recycling, SIB and extenders), even with no new technologies, the ambitious objective of replacing all ICEVs by EVs can effectively be reached. Furthermore, it can be done by preserving a substantial part of the raw material reserves if right technologies' combination is used.

Major actors in the sector can be made aware that by focusing as from now on these aspects they can:

- ensure sustainability of the planet
- and ensure sustainability of their business.

Also, development of innovative technologies can boost even more the complete process, businesses still have much to gain by investing into R&D. And that without having to fear a collapse of their business if they are not the first to discover the "brand new" battery technology.

Regarding the Scientific point of view, it is important to note that recycling remains a domain in which is worth putting efforts in. Various solutions are found by "simply" improving the recycling process of various materials.

Also, the use of extenders is an interesting approach as it mixes different technologies. This can push the scientists to drive their research even further in the domain of hybrid solutions. Those hybrid solutions could consist for example of electric power supplies with extenders, coupled with internal combustion engines powered by green fuel.

Thus, to conclude, the analysis made over the SDS highlights the need for innovative technologies' usage in EVs' industry. Considering this ambitious scenario, actual recycling rates predictions & battery chemistries are not sufficient. This model with its hypotheses is not sustainable in its rare materials usage. However, the tools aforementioned are already applicable. Including their gradual use, even SDS becomes possible. Therefore, rare materials depletion in EVs' industry depend on upcoming efforts by industry & governments. Those efforts alone could be sufficient to make an ambitious transition from ICEVs to EVs sustainable.

Bibliography

Abraham, K. M. (2020). How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts? ACS Energy Letters, 5(11), 3544–3547. https://doi.org/10.1021/acsenergylett.0c02181

Agence de l'Environnement et de la Maîtrise de l'Energie, Niels Warburg, Alexander Forell, Laura Guillon, Hélène Teulon, & Benjamin Canaguier. (2013). ELABORATION SELON LES PRINCIPES DES ACV DES BILANS ENERGETIQUES, DES EMISSIONS DE GAZ A EFFET DE SERRE ET DES AUTRES IMPACTS ENVIRONNEMENTAUX INDUITS PAR L'ENSEMBLE DES FILIERES DE VEHICULES ELECTRIQUES ET DE VEHICULES THERMIQUES, VP DE SEGMENT B (CITADINE POLYVALENTE) ET VUL A L'HORIZON 2012 ET 2020. https://www.ademe.fr/sites/default/files/assets/documents/ademe_-_acv_comparative_ve-vt_-_resume_du_rapport_final.pdf

Berckmans, G., Messagie, M., Smekens, J., Omar, N., & Vanhaverbeke, L. (2017). Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. Energies, 10(9), 1314. https://doi.org/10.3390/en10091314

Bethoux, O. (2020). Hydrogen Fuel Cell Road Vehicles: State of the Art and Perspectives. Energies, 13(21), 1–28. https://doi.org/10.3390/en13215843

Chan, K. H., Anawati, J., Malik, M., & Azimi, G. (2021). Closed-Loop Recycling of Lithium, Cobalt, Nickel, and Manganese from Waste Lithium-Ion Batteries of Electric Vehicles. ACS Sustainable Chemistry & Engineering, 9(12), 4398–4410. https://doi.org/10.1021/acssuschemeng.0c06869

Chayambuka, K., Mulder, G., Danilov, D. L., & Notten, P. H. L. (2020). From Li-Ion Batteries toward Na-Ion Chemistries: Challenges and Opportunities. Advanced Energy Materials, 10(38), 2001310. https://doi.org/10.1002/aenm.202001310

Chen, J., Wu, J., Wang, X., Zhou, A., & Yang, Z. (2021). Research progress and application prospect of solid-state electrolytes in commercial lithium-ion power batteries. Energy Storage Materials, 35, 70–87. https://doi.org/10.1016/j.ensm.2020.11.017

Christidis, P., & Focas, C. (2019). Factors Affecting the Uptake of Hybrid and Electric Vehicles in the European Union. Energies, 12(18), 3414. https://doi.org/10.3390/en12183414

Ciez, R. E., & Whitacre, J. F. (2019). Examining different recycling processes for lithium-ion batteries. Nature Sustainability, 2(2), 148–156. https://doi.org/10.1038/s41893-019-0222-5

Costa, C., Barbosa, J., Castro, H., Gonçalves, R., & Lanceros-Méndez, S. (2021). Electric vehicles: To what extent are environmentally friendly and cost effective? – Comparative study by european countries. Renewable and Sustainable Energy Reviews, 151, 111548. https://doi.org/10.1016/j.rser.2021.111548

Dai, Q., Kelly, J. C., Gaines, L., & Wang, M. (2019). Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. Batteries, 5(2), 48. https://doi.org/10.3390/batteries5020048

Duffner, F., Wentker, M., Greenwood, M., & Leker, J. (2020). Battery cost modeling: A review and directions for future research. Renewable and Sustainable Energy Reviews, 127, 109872. https://doi.org/10.1016/j.rser.2020.109872

Edelenbosch, O. Y., Hof, A. F., Nykvist, B., Girod, B., & van Vuuren, D. P. (2018). Transport electrification: the effect of recent battery cost reduction on future emission scenarios. Climatic Change, 151(2), 95–108. https://doi.org/10.1007/s10584-018-2250-y

Evarts, E. C. (2015). Lithium batteries: To the limits of lithium. Nature, 526(7575), S93–S95. https://doi.org/10.1038/526s93a

Farfan-Cabrera, L. I. (2019). Tribology of electric vehicles: A review of critical components, current state and future improvement trends. Tribology International, 138, 473–486. https://doi.org/10.1016/j.triboint.2019.06.029

figshare. (2020). Stock dynamics model and result analysis for future material demand for automotive lithium-based batteries.xlsx [Dataset]. https://figshare.com/articles/software/Stock_dynamics_model_and_result_analysis_for_future_material_demand_for_automotive_lithium-based_batteries_xlsx/13042001/1

Fu, X., Beatty, D. N., Gaustad, G. G., Ceder, G., Roth, R., Kirchain, R. E., Bustamante, M., Babbitt, C., & Olivetti, E. A. (2020). Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. Environmental Science & Technology, 54(5), 2985–2993. https://doi.org/10.1021/acs.est.9b04975

Gaines, L. (2019). Profitable Recycling of Low-Cobalt Lithium-Ion Batteries Will Depend on New Process Developments. One Earth, 1(4), 413–415. https://doi.org/10.1016/j.oneear.2019.12.001

Gross, R., Hanna, R., Gambhir, A., Heptonstall, P., & Speirs, J. (2018). How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. Energy Policy, 123, 682–699. https://doi.org/10.1016/j.enpol.2018.08.061

Günther, H. O., Kannegiesser, M., & Autenrieb, N. (2015). The role of electric vehicles for supply chain sustainability in the automotive industry. Journal of Cleaner Production, 90, 220–233. https://doi.org/10.1016/j.jclepro.2014.11.058

Habib, K., Hansdóttir, S. T., & Habib, H. (2020). Critical metals for electromobility: Global demand scenarios for passenger vehicles, 2015–2050. Resources, Conservation and Recycling, 154, 104603. https://doi.org/10.1016/j.resconrec.2019.104603

Hannan, M. A., Hoque, M. M., Hussain, A., Yusof, Y., & Ker, P. J. (2018). State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications: Issues and Recommendations. IEEE Access, 6, 19362–19378. https://doi.org/10.1109/access.2018.2817655

Hannan, M., Hoque, M., Mohamed, A., & Ayob, A. (2017). Review of energy storage systems for electric vehicle applications: Issues and challenges. Renewable and Sustainable Energy Reviews, 69, 771–789. https://doi.org/10.1016/j.rser.2016.11.171

Haque, N., Hughes, A., Lim, S., & Vernon, C. (2014). Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact. Resources, 3(4), 614–635. https://doi.org/10.3390/resources3040614

Heitel, S., Seddig, K., Gómez Vilchez, J. J., & Jochem, P. (2020). Global electric car market deployment considering endogenous battery price development. Technological Learning in the Transition to a Low-Carbon Energy System, 281–305. https://doi.org/10.1016/b978-0-12-818762-3.00015-7

Helbig, C., Bradshaw, A. M., Wietschel, L., Thorenz, A., & Tuma, A. (2018). Supply risks associated with lithium-ion battery materials. Journal of Cleaner Production, 172, 274–286. https://doi.org/10.1016/j.jclepro.2017.10.122

Helmers, E. (2014). Possible Resource Restrictions for the Future Large-Scale Production of Electric Cars. Competition and Conflicts on Resource Use, 121–131. https://doi.org/10.1007/978-3-319-10954-1_9

Helmers, E., & Weiss, M. (2017). Advances and critical aspects in the life-cycle assessment of battery electric cars. Energy and Emission Control Technologies, Volume 5, 1–18. https://doi.org/10.2147/eect.s60408

Hsieh, I. Y. L., Pan, M. S., Chiang, Y. M., & Green, W. H. (2019). Learning only buys you so much: Practical limits on battery price reduction. Applied Energy, 239, 218–224. https://doi.org/10.1016/j.apenergy.2019.01.138

Iglesias-Émbil, M., Valero, A., Ortego, A., Villacampa, M., Vilaró, J., & Villalba, G. (2020). Raw material use in a battery electric car – a thermodynamic rarity assessment. Resources, Conservation and Recycling, 158, 104820. https://doi.org/10.1016/j.resconrec.2020.104820

International Council on Clean Transportation Europe, & Georg Bieker. (2021, July). A GLOBAL COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS. https://www.avere.org/wp-content/uploads/2021/07/Global-LCA-passenger-cars-jul2021-0.pdf

International Council on Clean Transportation, Miller, J., Khan, T., Yang, Z., Sen, A., & Kohli, S. (2021, December). Decarbonizing road transport by 2050 Accelerating the global transition to zero-emission vehicles. https://theicct.org/sites/default/files/publications/ZEVTC_Accelerating-transition_dec2021.pdf

International Energy Agency. (2020). Global EV Outlook 2020: Entering the decade of electric drive? https://www.iea.org/reports/global-ev-outlook-2020

IVL Swedish Environmental Research Institute: Stockholm, Emilsson, E., & Dahllöf, L. (2019). Lithium-ion vehicle battery production. https://www.ivl.se/download/18.694ca0617a1de98f473464/1628416191286/FULLTEXT01.pdf

Jetin, B. (2020). Who will control the electric vehicle market. International Journal of Automotive Technology and Management, 20(2), 156. https://doi.org/10.1504/ijatm.2020.108584

Kavanagh, L., Keohane, J., Garcia Cabellos, G., Lloyd, A., & Cleary, J. (2018). Global Lithium Sources—Industrial Use and Future in the Electric Vehicle Industry: A Review. Resources, 7(3), 57. https://doi.org/10.3390/resources7030057

Knobloch, F., Hanssen, S. V., Lam, A., Pollitt, H., Salas, P., Chewpreecha, U., Huijbregts, M. A. J., & Mercure, J. F. (2020). Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nature Sustainability, 3(6), 437–447. https://doi.org/10.1038/s41893-020-0488-7

Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., Prenninger, P., Coosemans, T., Neugebauer, S., & Verhoeve, W. (2020). EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios. Energy Policy, 138, 111224. https://doi.org/10.1016/j.enpol.2019.111224

Laadjal, K., & Cardoso, A. J. M. (2021). Estimation of Lithium-Ion Batteries State-Condition in Electric Vehicle Applications: Issues and State of the Art. Electronics, 10(13), 1588. https://doi.org/10.3390/electronics10131588

Li, C., Liu, L., Kang, J., Xiao, Y., Feng, Y., Cao, F. F., & Zhang, H. (2020). Pristine MOF and COF materials for advanced batteries. Energy Storage Materials, 31, 115–134. https://doi.org/10.1016/j.ensm.2020.06.005

Liu, X., Li, K., & Li, X. (2018). The Electrochemical Performance and Applications of Several Popular Lithium-ion Batteries for Electric Vehicles - A Review. Communications in Computer and Information Science, 201–213. https://doi.org/10.1007/978-981-13-2381-2_19

Manzetti, S., & Mariasiu, F. (2015). Electric vehicle battery technologies: From present state to future systems. Renewable and Sustainable Energy Reviews, 51, 1004–1012. https://doi.org/10.1016/j.rser.2015.07.010

Marques, P., Garcia, R., Kulay, L., & Freire, F. (2019). Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. Journal of Cleaner Production, 229, 787–794. https://doi.org/10.1016/j.jclepro.2019.05.026

Mayyas, A., Steward, D., & Mann, M. (2019). The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. Sustainable Materials and Technologies, 19. https://doi.org/10.1016/j.susmat.2018.e00087

Miao, Y., Hynan, P., von Jouanne, A., & Yokochi, A. (2019). Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. Energies, 12(6), 1074. https://doi.org/10.3390/en12061074

Mo, J., & Jeon, W. (2018). The Impact of Electric Vehicle Demand and Battery Recycling on Price Dynamics of Lithium-Ion Battery Cathode Materials: A Vector Error Correction Model (VECM) Analysis. Sustainability, 10(8), 2870. https://doi.org/10.3390/su10082870

Morfeldt, J., Davidsson Kurland, S., & Johansson, D. J. (2021). Carbon footprint impacts of banning cars with internal combustion engines. Transportation Research Part D: Transport and Environment, 95, 102807. https://doi.org/10.1016/j.trd.2021.102807

Mossali, E., Picone, N., Gentilini, L., Rodrìguez, O., Pérez, J. M., & Colledani, M. (2020). Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments. Journal of Environmental Management, 264, 110500. https://doi.org/10.1016/j.jenvman.2020.110500

Muench, S., Wild, A., Friebe, C., Häupler, B., Janoschka, T., & Schubert, U. S. (2016). Polymer-Based Organic Batteries. Chemical Reviews, 116(16), 9438–9484. https://doi.org/10.1021/acs.chemrev.6b00070

National Renewable Energy Lab. (NREL), Golden, CO (United States), Igogo, Tsisilile, A., Sandor, Debra, L., Mayyas, Ahmad, T., & Engel-Cox, Jill. (2019, August). Supply Chain of Raw Materials Used in the Manufacturing of Light-Duty Vehicle Lithium-Ion Batteries. https://doi.org/10.2172/1560124

Natkunarajah, N., Scharf, M., & Scharf, P. (2015). Scenarios for the Return of Lithium-ion Batteries out of Electric Cars for Recycling. Procedia CIRP, 29, 740–745. https://doi.org/10.1016/j.procir.2015.02.170

Nguyen, R. T., Eggert, R. G., Severson, M. H., & Anderson, C. G. (2021). Global Electrification of Vehicles and Intertwined Material Supply Chains of Cobalt, Copper and Nickel. Resources, Conservation and Recycling, 167, 105198. https://doi.org/10.1016/j.resconrec.2020.105198

Olafsdottir, A. H., & Sverdrup, H. U. (2021). Modelling Global Nickel Mining, Supply, Recycling, Stocks-in-Use and Price Under Different Resources and Demand Assumptions for 1850–2200. Mining, Metallurgy & Exploration, 38(2), 819–840. https://doi.org/10.1007/s42461-020-00370-y

Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. Joule, 1(2), 229–243. https://doi.org/10.1016/j.joule.2017.08.019

Or, T., Gourley, S. W. D., Kaliyappan, K., Yu, A., & Chen, Z. (2020). Recycling of mixed cathode lithium-ion batteries for electric vehicles: Current status and future outlook. Carbon Energy, 2(1), 6–43. https://doi.org/10.1002/cey2.29

Pant, D., & Dolker, T. (2017). Green and facile method for the recovery of spent Lithium Nickel Manganese Cobalt Oxide (NMC) based Lithium ion batteries. Waste Management, 60, 689–695. https://doi.org/10.1016/j.wasman.2016.09.039

Pehlken, A., Albach, S., & Vogt, T. (2015). Is there a resource constraint related to lithium ion batteries in cars? The International Journal of Life Cycle Assessment, 22(1), 40–53. https://doi.org/10.1007/s11367-015-0925-4

Pereirinha, P. G., González, M., Carrilero, I., Anseán, D., Alonso, J., & Viera, J. C. (2018). Main Trends and Challenges in Road Transportation Electrification. Transportation Research Procedia, 33, 235–242. https://doi.org/10.1016/j.trpro.2018.10.096

Peters, J., & Weil, M. (2016). A Critical Assessment of the Resource Depletion Potential of Current and Future Lithium-Ion Batteries. Resources, 5(4), 46. https://doi.org/10.3390/resources5040046

Porzio, J., & Scown, C. D. (2021). Life-Cycle Assessment Considerations for Batteries and Battery Materials. Advanced Energy Materials, 11(33), 2100771. https://doi.org/10.1002/aenm.202100771

Publications Office of the European Union. (2018). Cobalt: demand-supply balances in the transition to electric mobility. https://doi.org/10.2760/97710

Quinteros-Condoretty, A. R., Golroudbary, S. R., Albareda, L., Barbiellini, B., & Soyer, A. (2021). Impact of circular design of lithium-ion batteries on supply of lithium for electric cars towards a sustainable mobility and energy transition. Procedia CIRP, 100, 73–78. https://doi.org/10.1016/j.procir.2021.05.012

Raugei, M., & Winfield, P. (2019). Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. Journal of Cleaner Production, 213, 926–932. https://doi.org/10.1016/j.jclepro.2018.12.237

Reuter, B. (2016). Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles. International Journal on Interactive Design and Manufacturing (IJIDeM), 10(3), 217–227. https://doi.org/10.1007/s12008-016-0329-0

Ritchie, H., & Roser, M. (2020, May 11). CO2 and Greenhouse Gas Emissions. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions?source=post_page-----47fa6c394991----------------------

Schmid, M. (2020). Challenges to the European automotive industry in securing critical raw materials for electric mobility: the case of rare earths. Mineralogical Magazine, 84(1), 5–17. https://doi.org/10.1180/mgm.2020.9

Schröer, P., van Faassen, H., Nemeth, T., Kuipers, M., & Sauer, D. U. (2020). Challenges in modeling high power lithium titanate oxide cells in battery management systems. Journal of Energy Storage, 28, 101189. https://doi.org/10.1016/j.est.2019.101189

Sonoc, A., & Jeswiet, J. (2014). A Review of Lithium Supply and Demand and a Preliminary Investigation of a Room Temperature Method to Recycle Lithium Ion Batteries to Recover Lithium and Other Materials. Procedia CIRP, 15, 289–293. https://doi.org/10.1016/j.procir.2014.06.006

Statista. (2021a). Lithium-ion batteries worldwide (did-22772-1). https://www.statista.com/study/22772/lithium-ion-batteries-statista-dossier/

Statista. (2021b, July 23). Projected battery demand worldwide by application 2020–2030. https://www.statista.com/statistics/1103218/global-battery-demand-forecast/

Statista. (2021c, September 20). Global lithium demand volume by application 2020–2030. https://www.statista.com/statistics/1220158/global-lithium-demand-volume-by-application/

Sun, X., Li, Z., Wang, X., & Li, C. (2019). Technology Development of Electric Vehicles: A Review. Energies, 13(1), 90. https://doi.org/10.3390/en13010090

Swain, B. (2017). Recovery and recycling of lithium: A review. Separation and Purification Technology, 172, 388–403. https://doi.org/10.1016/j.seppur.2016.08.031

Tang, C., Sprecher, B., Tukker, A., & Mogollón, J. M. (2021). The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040. Resources Policy, 74, 102351. https://doi.org/10.1016/j.resourpol.2021.102351

Tayar, S. P., Yeste, M. P., Ramírez, M., Cabrera, G., Bevilaqua, D., Gatica, J. M., Vidal, H., Cauqui, M. N., & Cantero, D. (2020). Nickel recycling through bioleaching of a Ni/Al2O3 commercial catalyst. Hydrometallurgy, 195, 105350. https://doi.org/10.1016/j.hydromet.2020.105350

Terlouw, T., AlSkaif, T., Bauer, C., & van Sark, W. (2019). Multi-objective optimization of energy arbitrage in community energy storage systems using different battery technologies. Applied Energy, 239, 356–372. https://doi.org/10.1016/j.apenergy.2019.01.227

Tran, M. K., DaCosta, A., Mevawalla, A., Panchal, S., & Fowler, M. (2021). Comparative Study of Equivalent Circuit Models Performance in Four Common Lithium-Ion Batteries: LFP, NMC, LMO, NCA. Batteries, 7(3), 51. https://doi.org/10.3390/batteries7030051

Tran, M. K., Sherman, S., Samadani, E., Vrolyk, R., Wong, D., Lowery, M., & Fowler, M. (2020). Environmental and Economic Benefits of a Battery Electric Vehicle Powertrain with a Zinc–Air Range Extender in the Transition to Electric Vehicles. Vehicles, 2(3), 398–412. https://doi.org/10.3390/vehicles2030021

Turcheniuk, K., Bondarev, D., Singhal, V., & Yushin, G. (2018). Ten years left to redesign lithium-ion batteries. Nature, 559(7715), 467–470. https://doi.org/10.1038/d41586-018-05752-3

Valero, A., Calvo, G., & Ortego, A. (2018). Material bottlenecks in the future development of green technologies. Renewable and Sustainable Energy Reviews, 93, 178–200. https://doi.org/10.1016/j.rser.2018.05.041

Weil, M., Ziemann, S., & Peters, J. (2018). The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles. Behaviour of Lithium-Ion Batteries in Electric Vehicles, 59–74. https://doi.org/10.1007/978-3-319-69950-9_3

Wood, M., Li, J., Ruther, R. E., Du, Z., Self, E. C., Meyer, H. M., Daniel, C., Belharouak, I., & Wood, D. L. (2020). Chemical stability and long-term cell performance of low-cobalt, Ni-Rich cathodes prepared by aqueous processing for high-energy Li-Ion batteries. Energy Storage Materials, 24, 188–197. https://doi.org/10.1016/j.ensm.2019.08.020

Wu, D., Ren, J., Davies, H., Shang, J., & Haas, O. (2019). Intelligent Hydrogen Fuel Cell Range Extender for Battery Electric Vehicles. World Electric Vehicle Journal, 10(2), 29. https://doi.org/10.3390/wevj10020029

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. Communications Materials, 1(1). https://doi.org/10.1038/s43246-020-00095-x

Young, K., Wang, C., Wang, L. Y., & Strunz, K. (2012). Electric Vehicle Battery Technologies. Electric Vehicle Integration into Modern Power Networks, 15–56. https://doi.org/10.1007/978-1-4614-0134-6_2

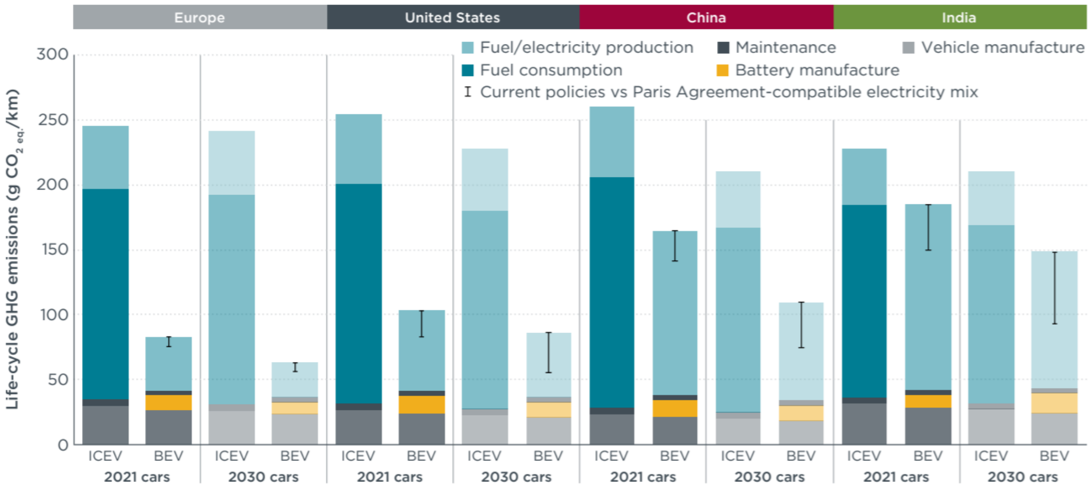
Zeng, X., Li, M., Abd El-Hady, D., Alshitari, W., Al-Bogami, A. S., Lu, J., & Amine, K. (2019). Commercialization of Lithium Battery Technologies for Electric Vehicles. Advanced Energy Materials, 9(27), 1900161. https://doi.org/10.1002/aenm.201900161

Zhang, W., Zhang, F., Ming, F., & Alshareef, H. N. (2019). Sodium-ion battery anodes: Status and future trends. EnergyChem, 1(2), 1–43. https://doi.org/10.1016/j.enchem.2019.100012

Ziemann, S., Müller, D. B., Schebek, L., & Weil, M. (2018). Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. Resources, Conservation and Recycling, 133, 76–85. https://doi.org/10.1016/j.resconrec.2018.01.031

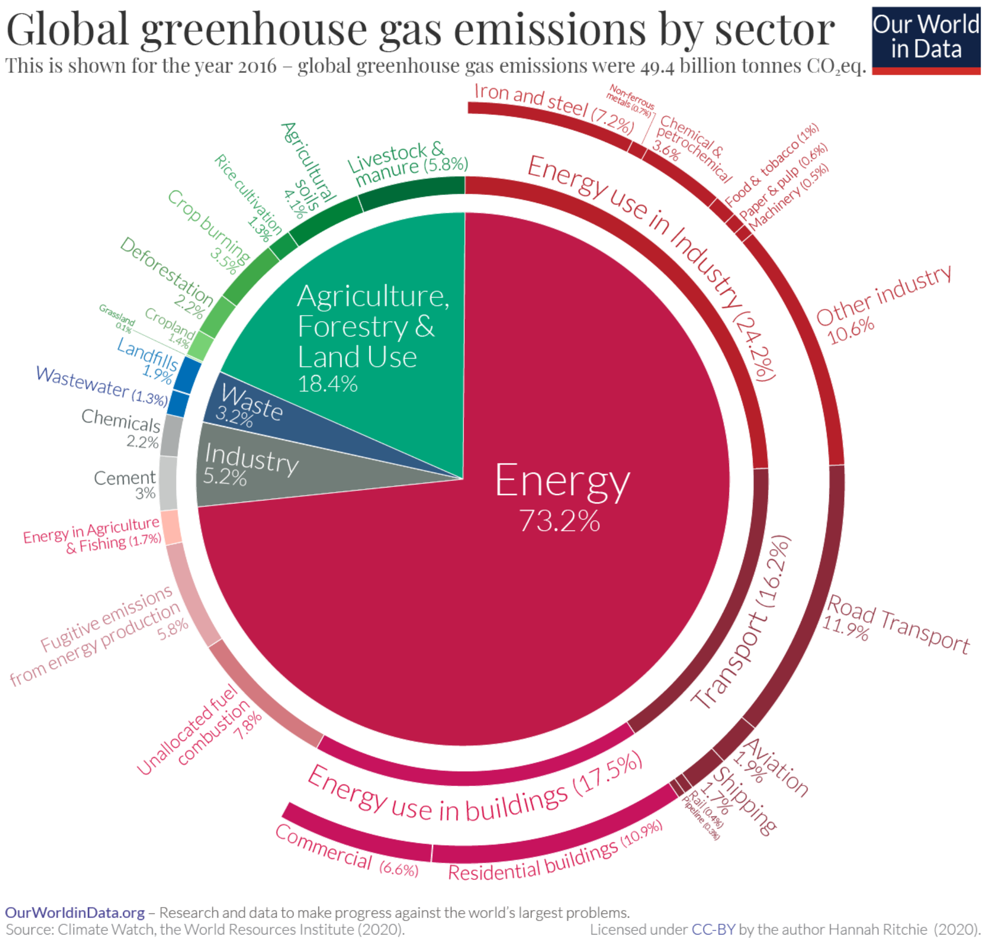
Appendix List

I. <u>Lifecycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030.</u>



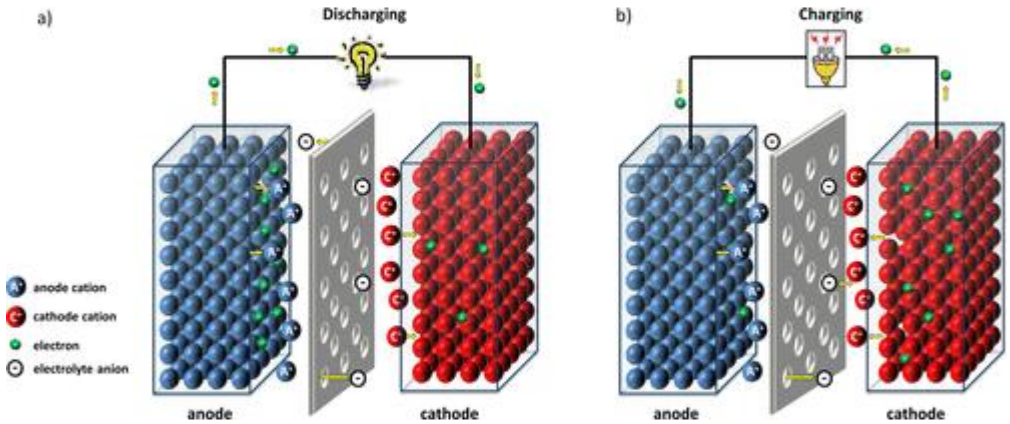
(International Council on Clean Transportation Europe & Georg Bieker, 2021)

II. <u>Global greenhouse gas emissions by sector.</u>



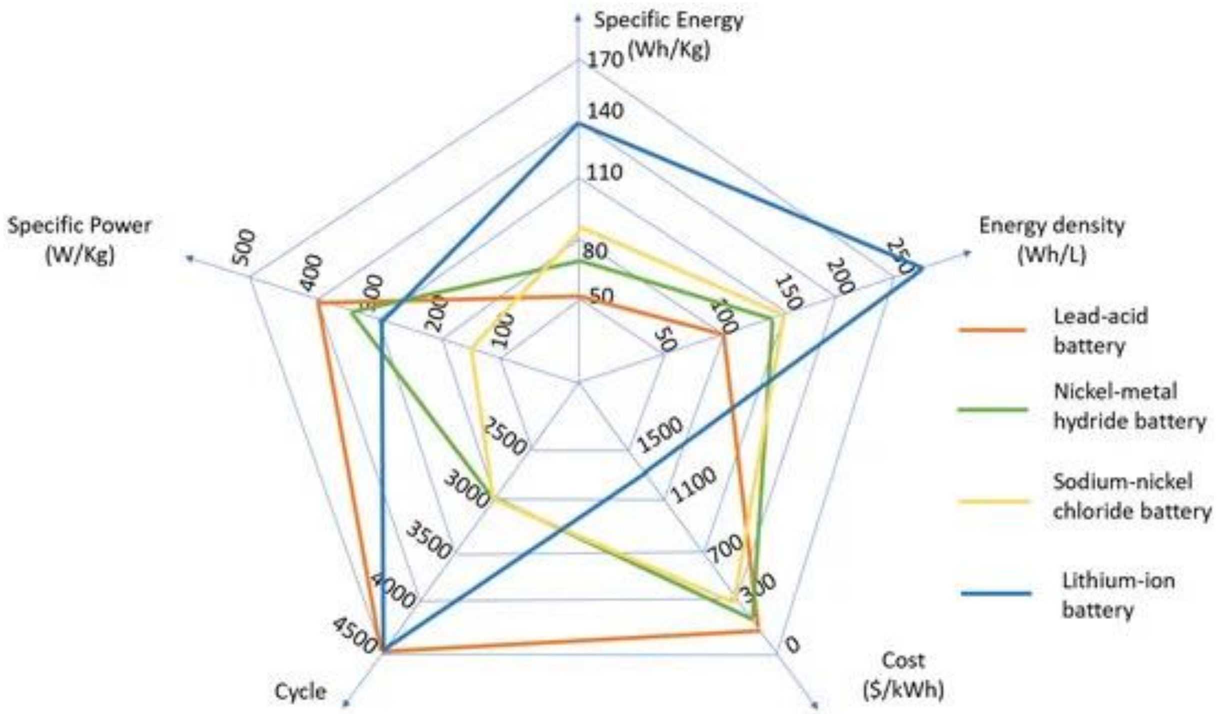
(Ritchie & Roser, 2020).

III. Schematic representation of the (a) discharging and (b) charging process of a metal-based secondary battery.



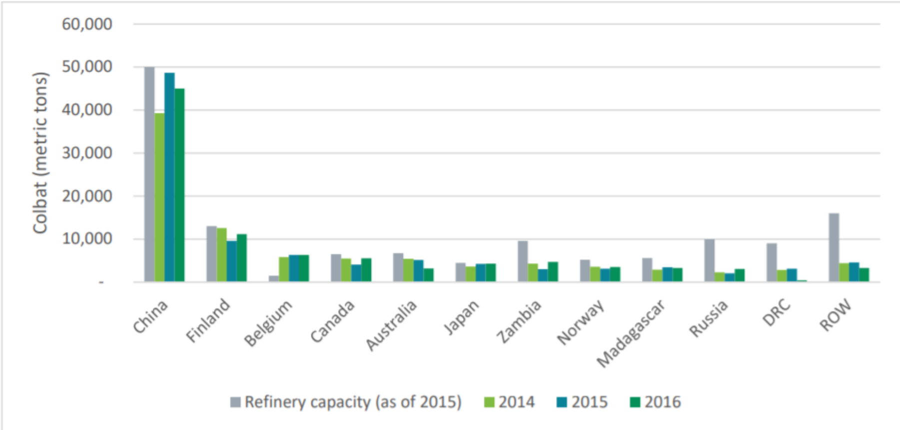
(Muench et al., 2016)

IV. Comparison of the characteristics of various power batteries.



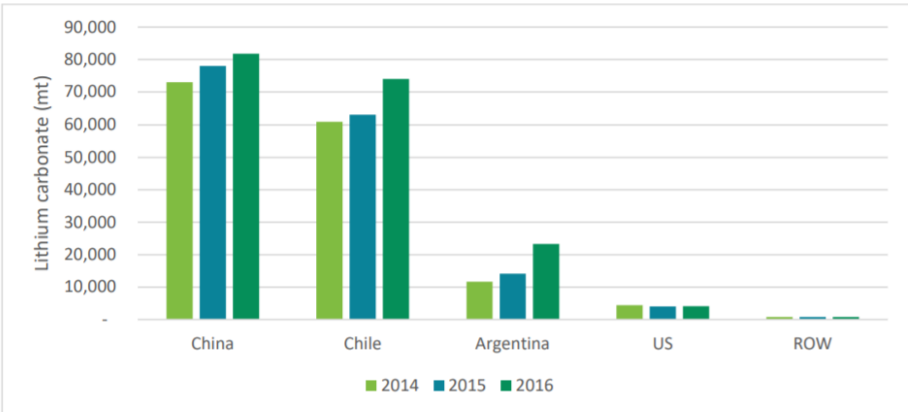
(Sun et al., 2019)

V. Refinery capacity and production of cobalt.



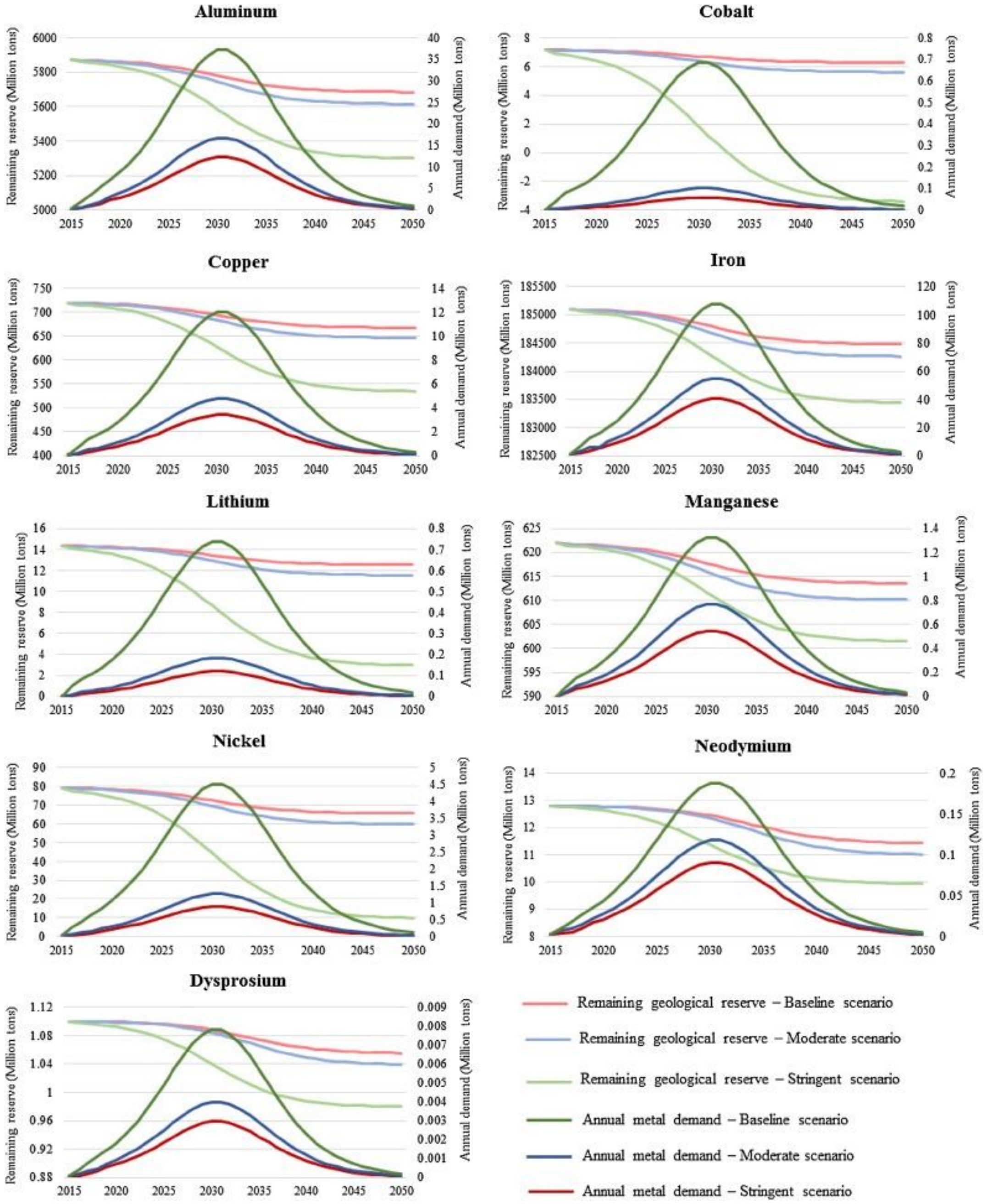
(National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019)

VI. Lithium carbonate production.



(National Renewable Energy Lab. (NREL), Golden, CO (United States) et al., 2019).

VII. Annual demand and the resulting amount of geological reserves of different metals considered in this study for the baseline, moderate and stringent scenarios.



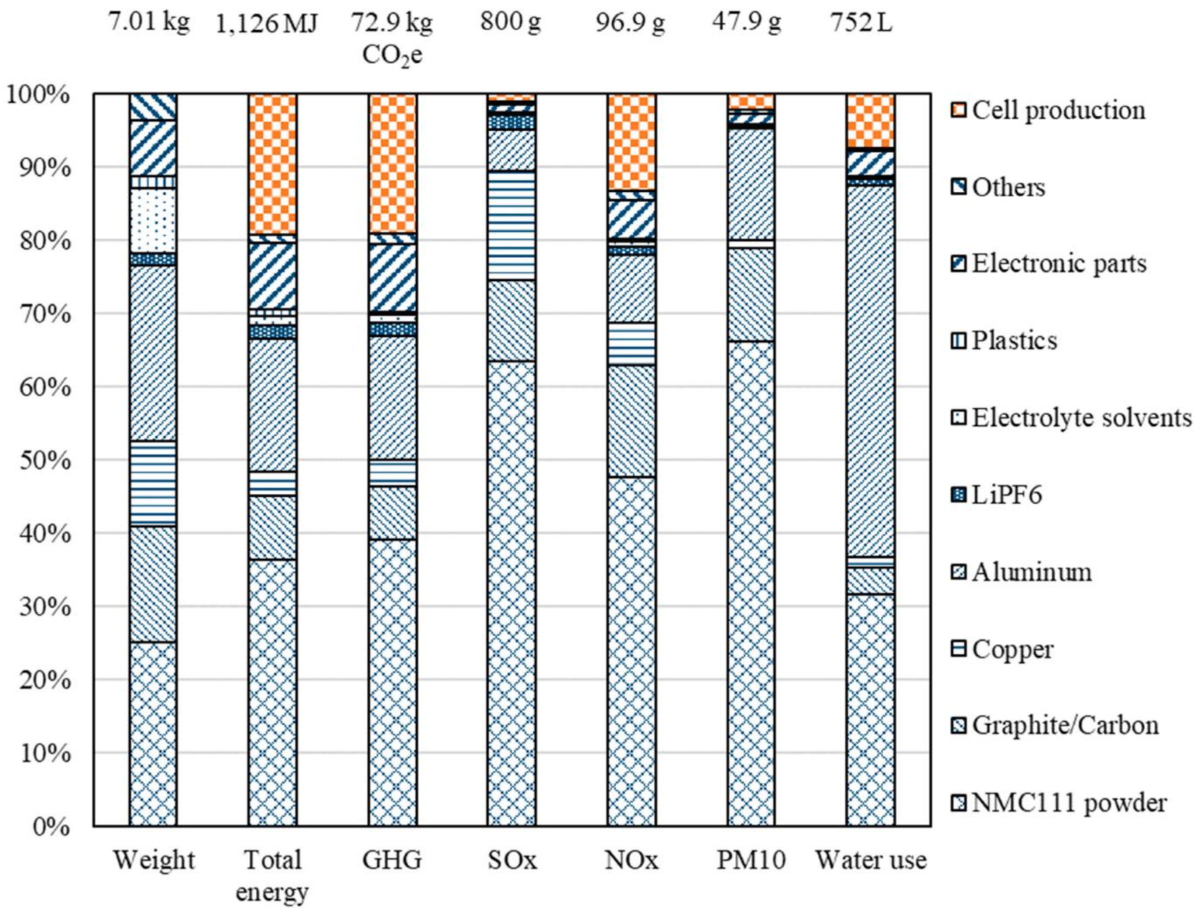
(Habib et al., 2020)

VIII. Recovery rates of Li and Co from spent LIBs.

Leaching agents	Ref.	Metal recovery rates		
		Li(%)	Co(%)	
Inorganic	$H_2SO_4/HNO_3/HCl$	Joulié et al., 2014	>80	100
	$H_2SO_4 + NaHSO_3$	Meshram et al., 2015	96.7	91.6
	$H_2SO_4 + H_2O_2$	He et al., 2017	>99.7	>99.7
	$NH_3 + (NH_4)_2SO_3 + (NH_4)_2CO_3$	Ku et al., 2016	–	80
Organic	Oxalate	Zeng et al., 2015	98	97
	Ascorbic acid	Li et al., 2012	98	95
	Acetic acid	Golmohammadzadeh et al., 2017	75	30
	Lactic acid + H_2O_2	Li et al., 2017a	98	99
	Iminodiacetic acid + H_2O_2	Nayaka et al., 2016a	99	91
	Maleic acid		100	97
	DL-malic acid + H_2O_2	Golmohammadzadeh et al., 2017	91	84
	Citric acid + H_2O_2		92	84
	Citric acid + H_2O_2	Mishra et al., 2008	99	98
	Citric acid + H_2O_2	Li et al., 2010	100	90
	Citric acid + H_2O_2	Santana et al., 2017	100	100
	Citric acid + TW	Chen et al., 2015	98	96
	Succinic acid	Li et al., 2015	100	96
	Tartaric acid + H_2O_2	He et al., 2017	99.1	98.6
***I*norganic + organic**	Phosphoric acid + glucose	Nayaka et al., 2016b	100	98

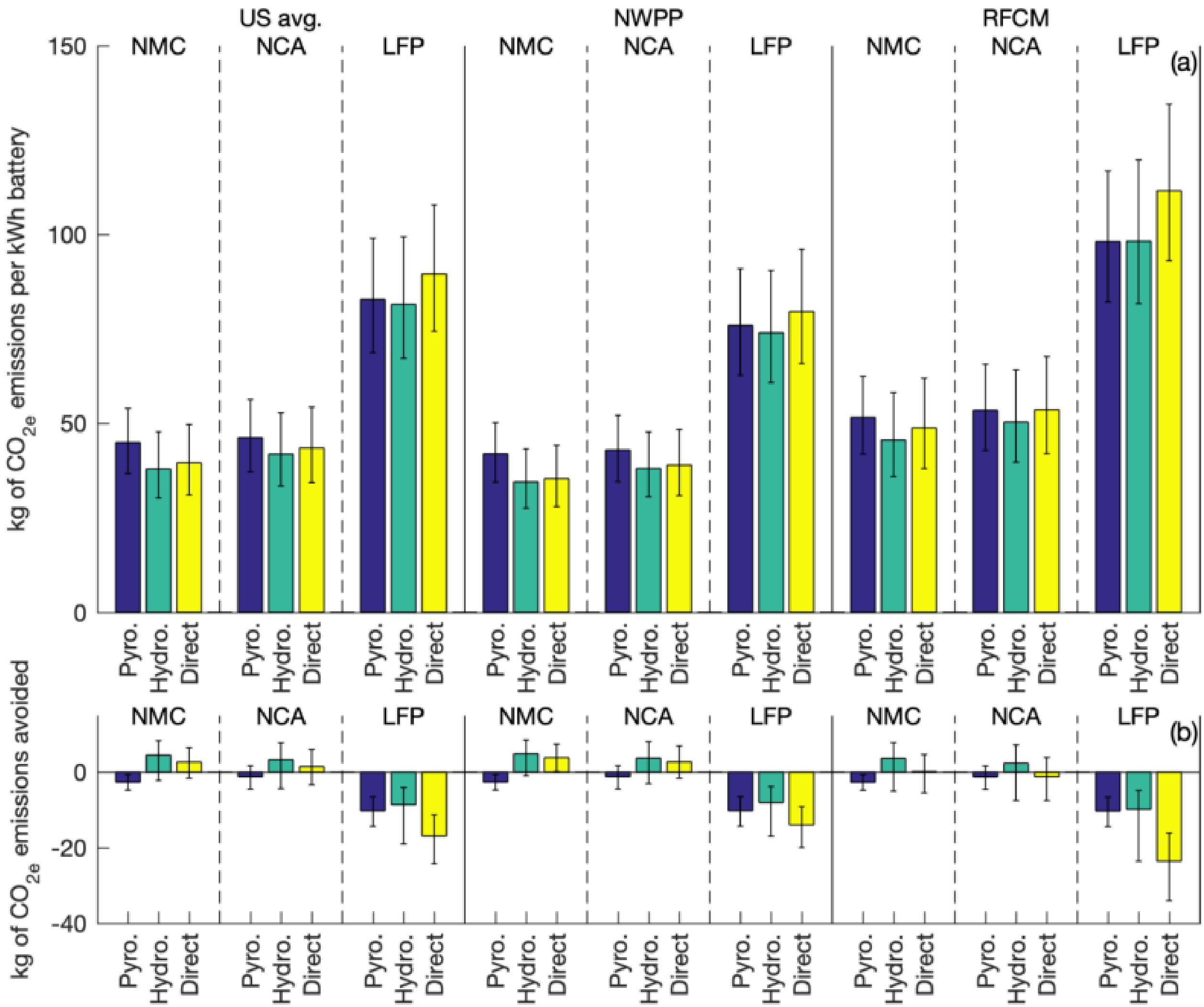
(Mossali et al., 2020)

IX. Cradle-to-gate impact breakdowns and bill of materials (BOM) of 1 kWh NMC111 battery. Blue denotes material inputs; orange denotes energy inputs for cell production.



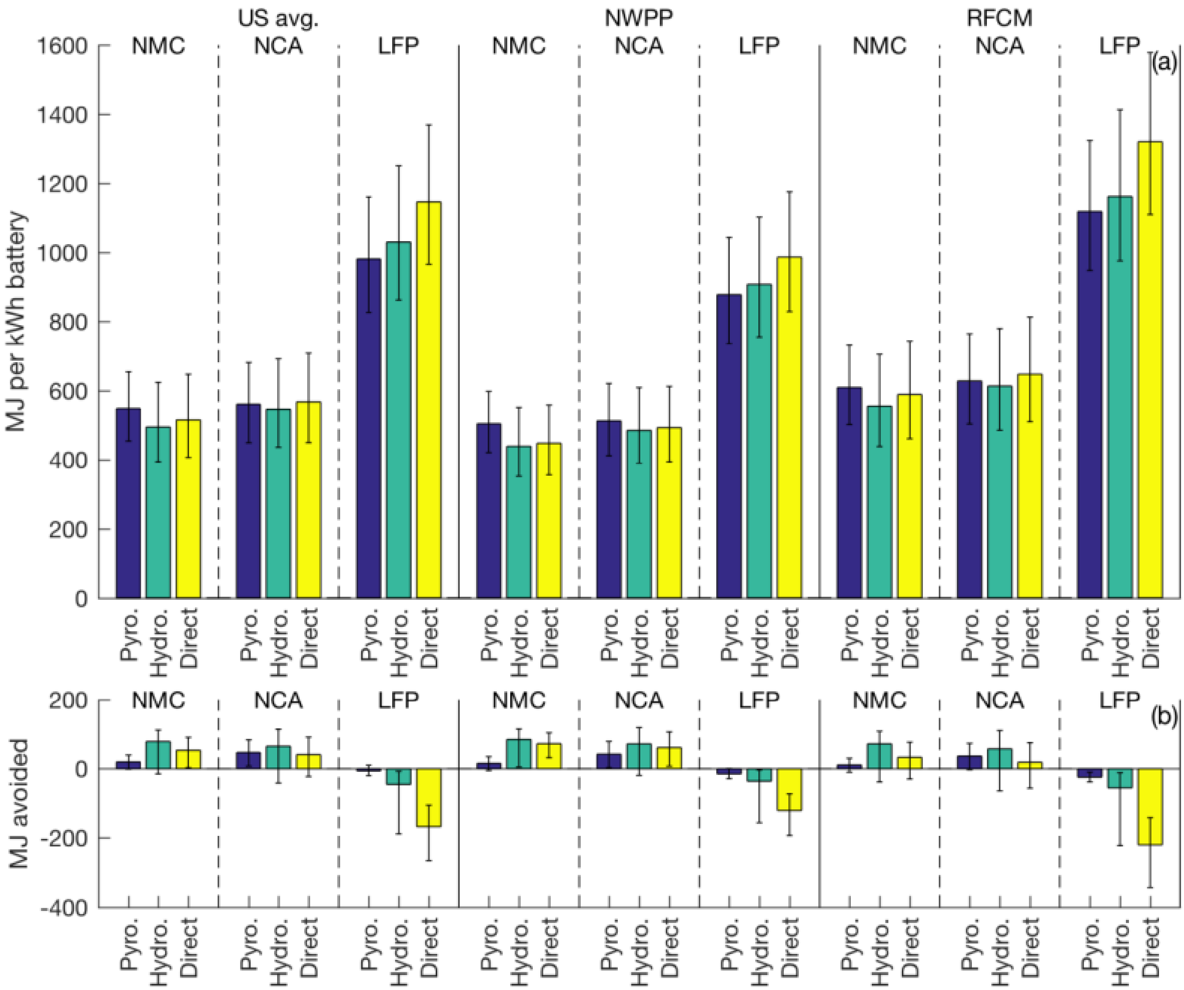
(Dai et al., 2019)

X. (a) Median and 95% confidence interval for CO2e emissions per kWh of battery for battery manufacturing and recycling. (b) median and 95% confidence interval of the net CO2e emissions avoided using difference recycling processes.



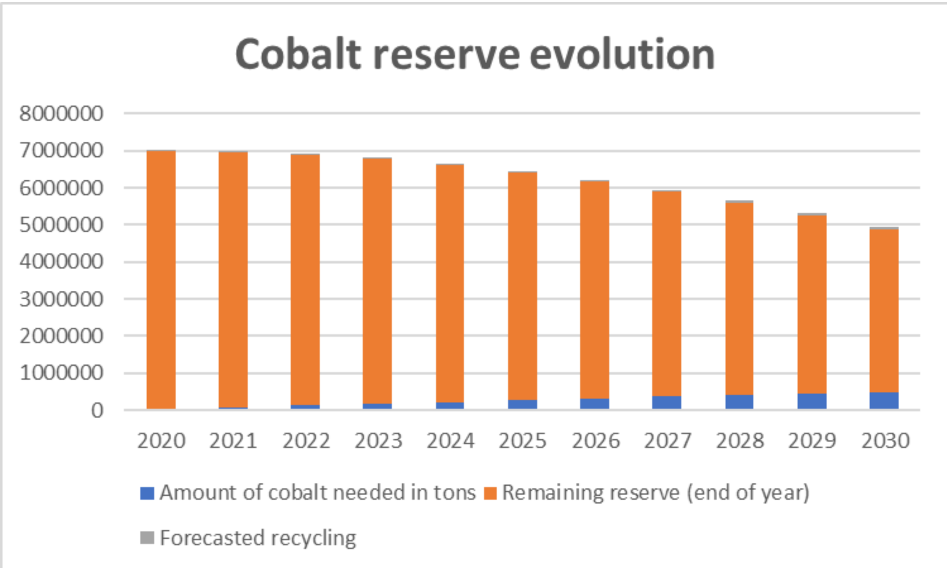
(Ciez & Whitacre, 2019)

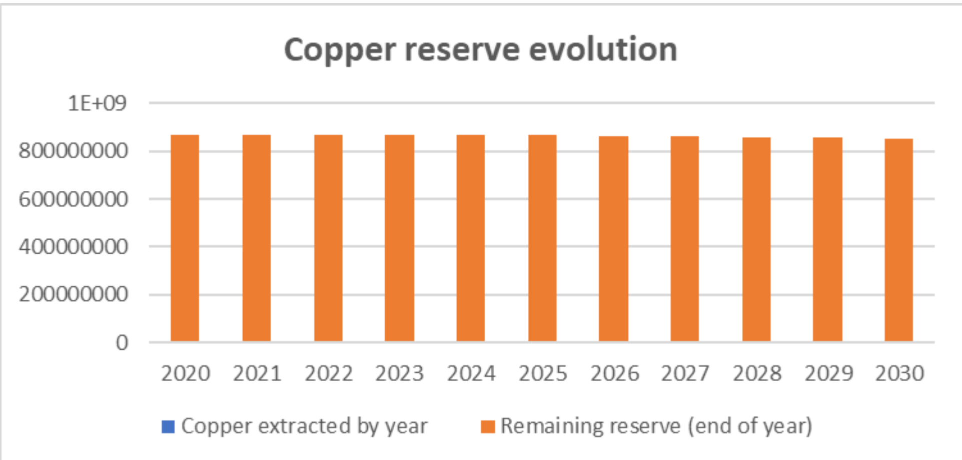
XI. <u>(a) Median and 95% confidence interval for MJ of embodied energy per kWh of battery for battery manufacturing and recycling. (b) median and 95% confidence interval of the net MJ embodied avoided using difference recycling processes.</u>

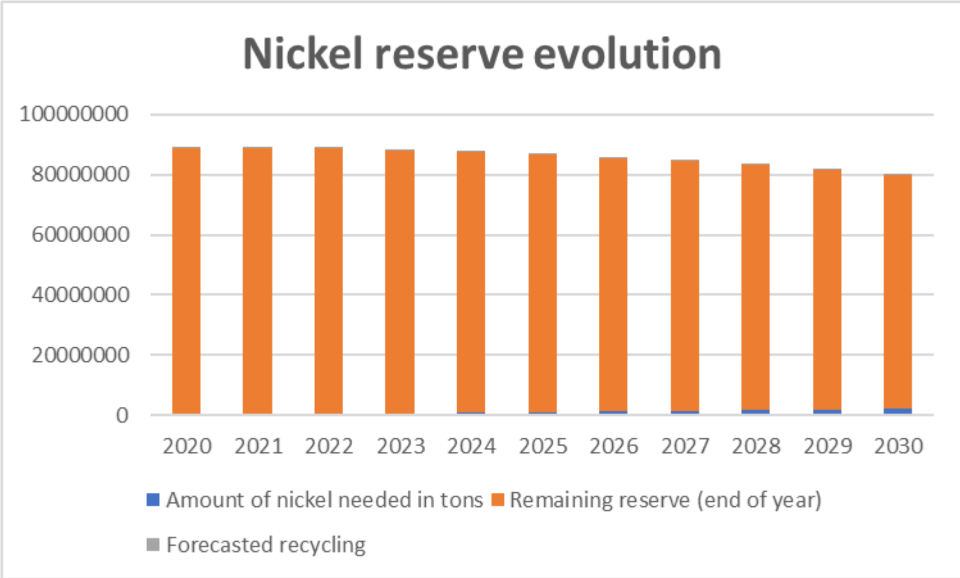


(Ciez & Whitacre, 2019)

XII. Lithium, Cobalt, Copper & Nickel reserve evolution caused by EVs production under predicted recycling assumption.

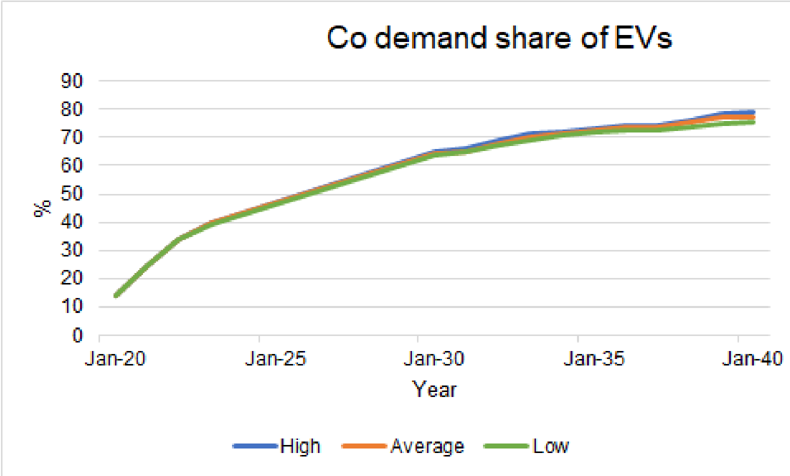


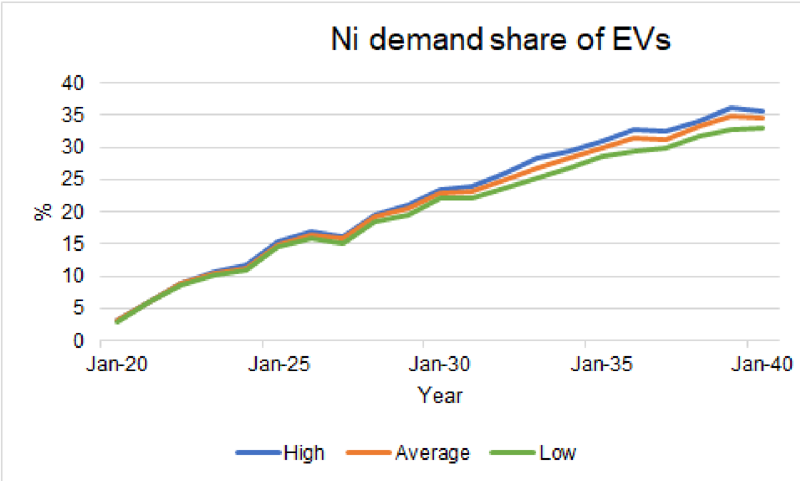


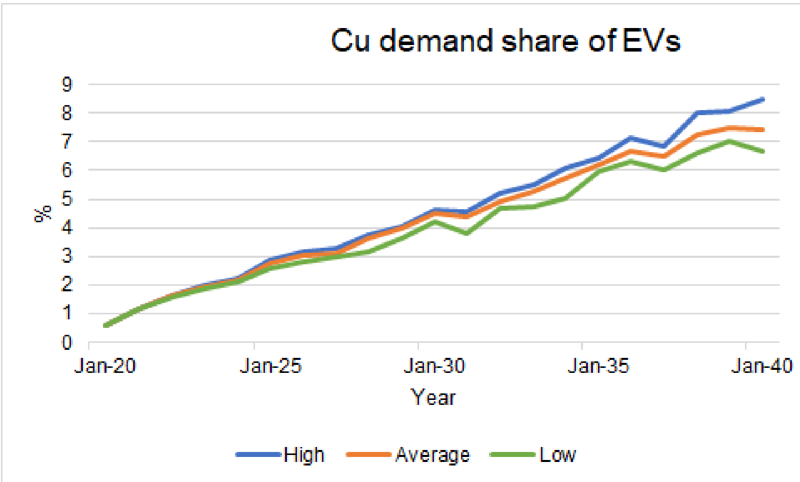


(Data sources: (Nguyen et al., 2021; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

XIII. Cobalt, Copper & Nickel EVs' demand share.

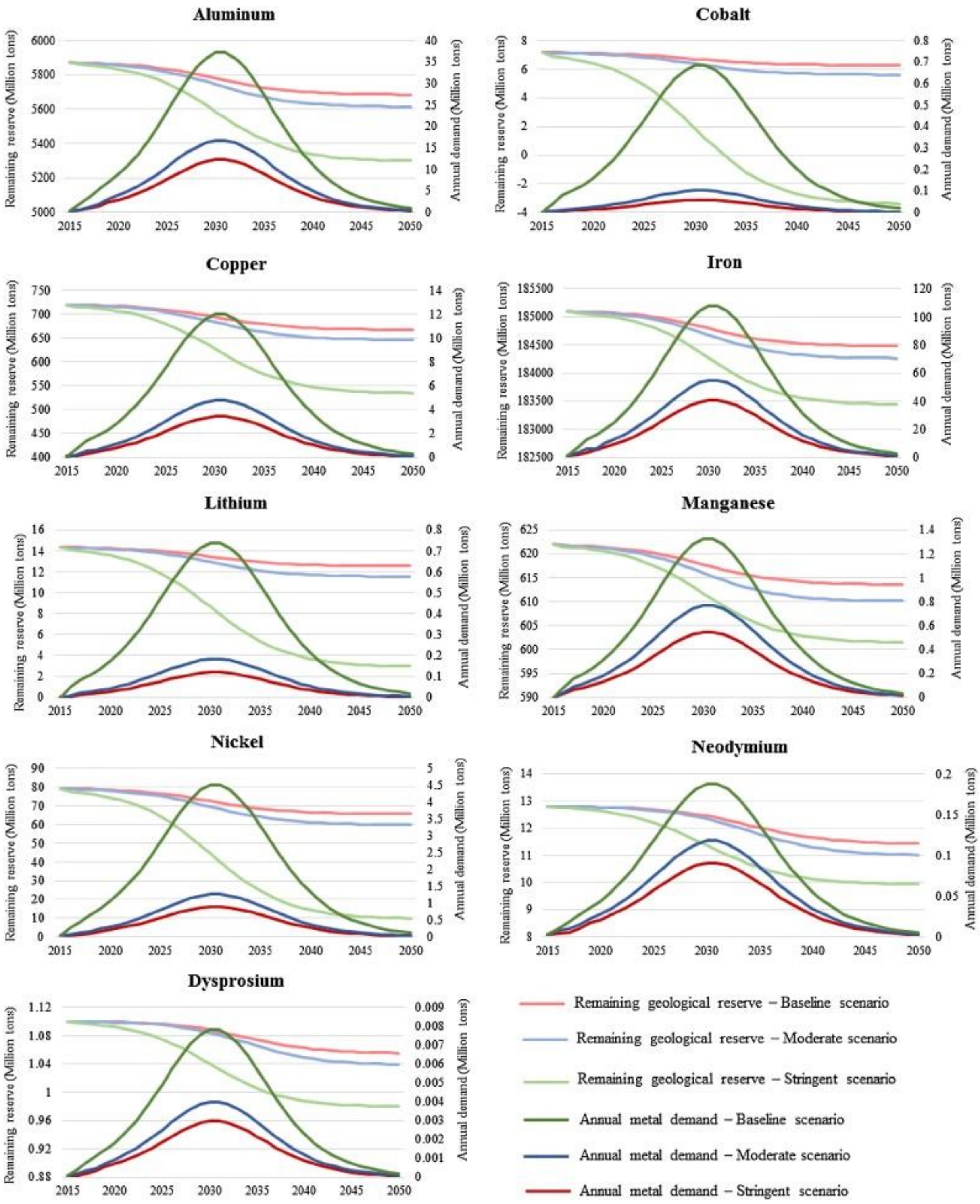






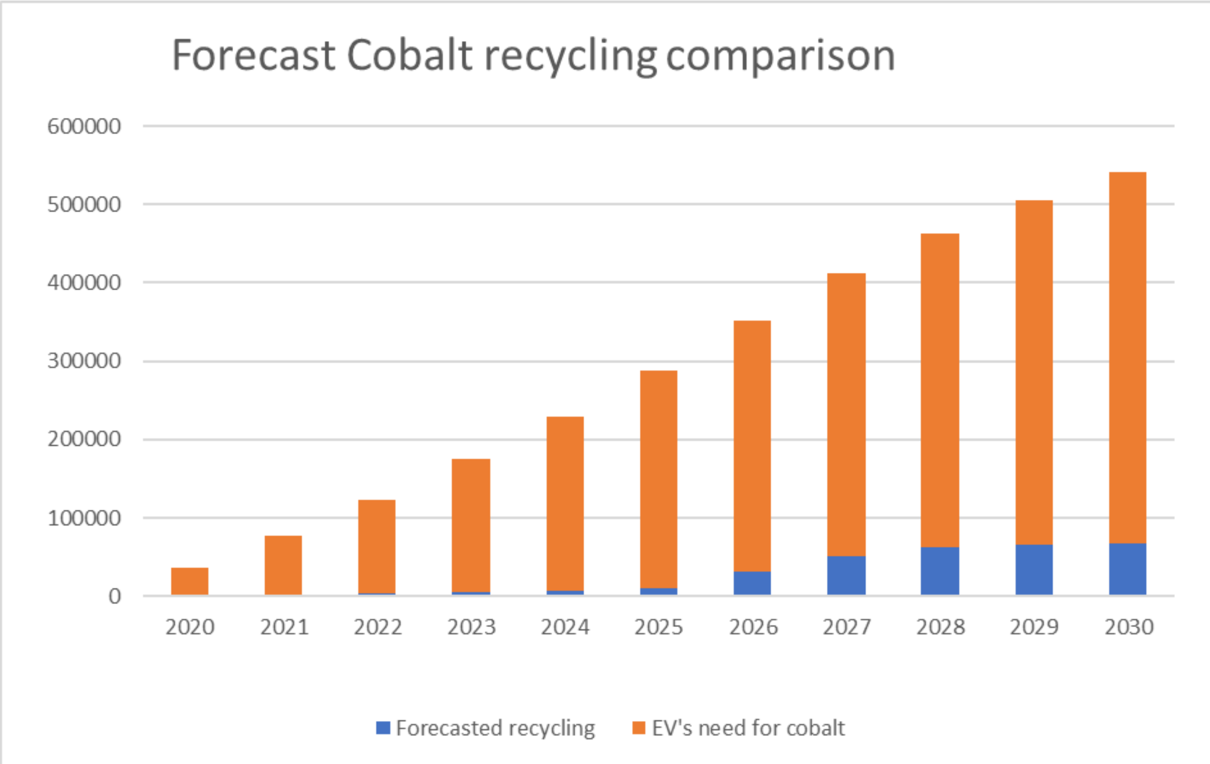
(Nguyen et al., 2021).

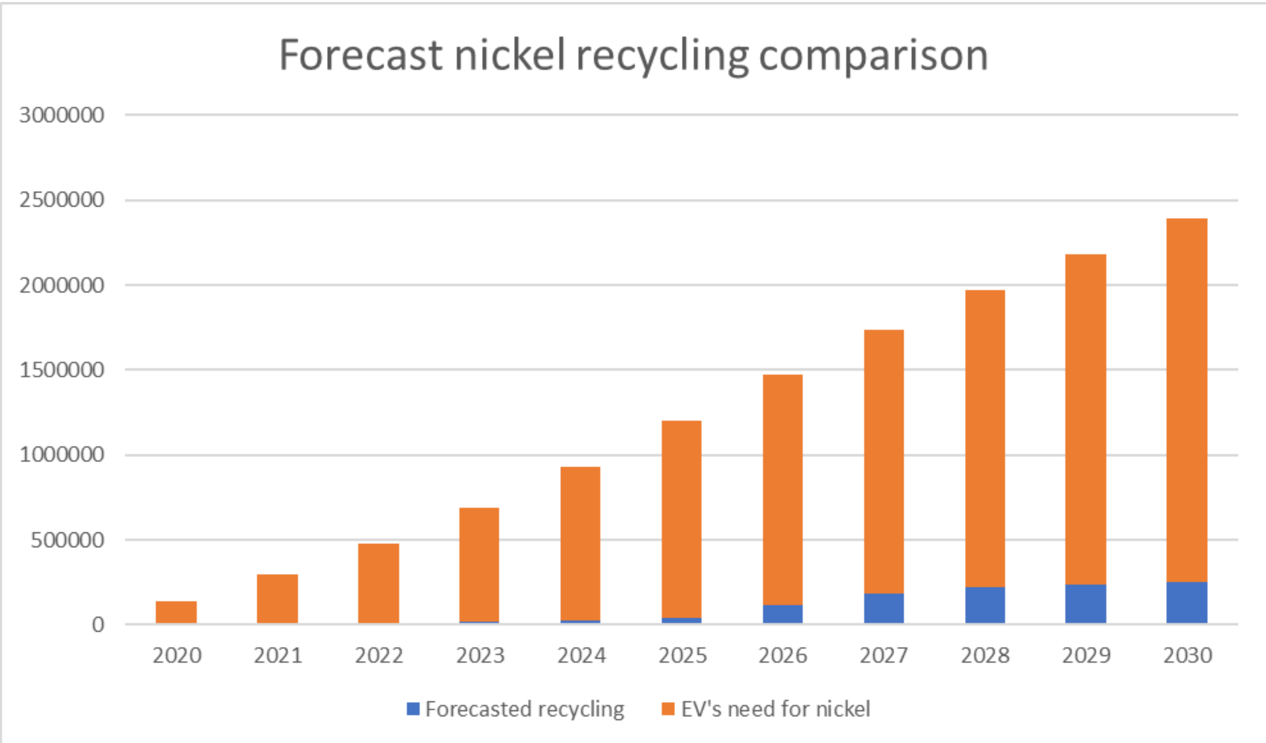
XIV. Rare materials demand and depletion.

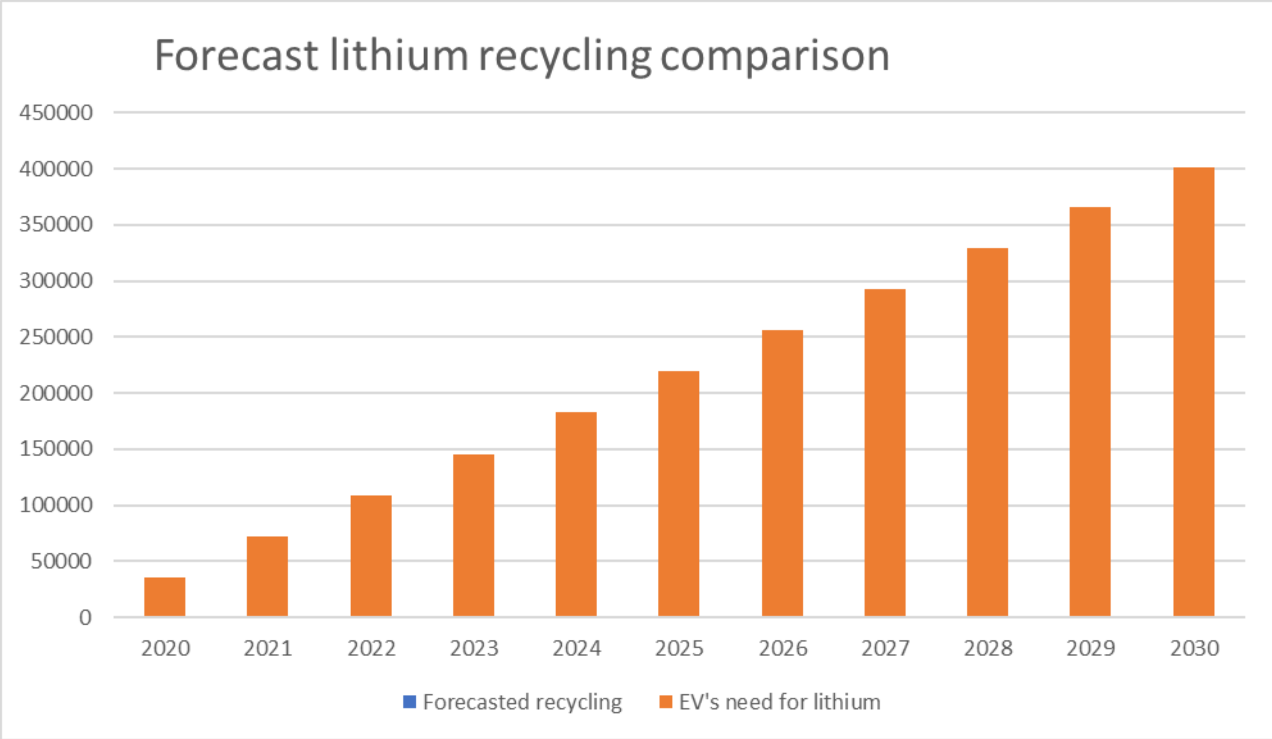


(Habib et al., 2020)

XV. Share of predicted rare materials recycling compared with EVs production.

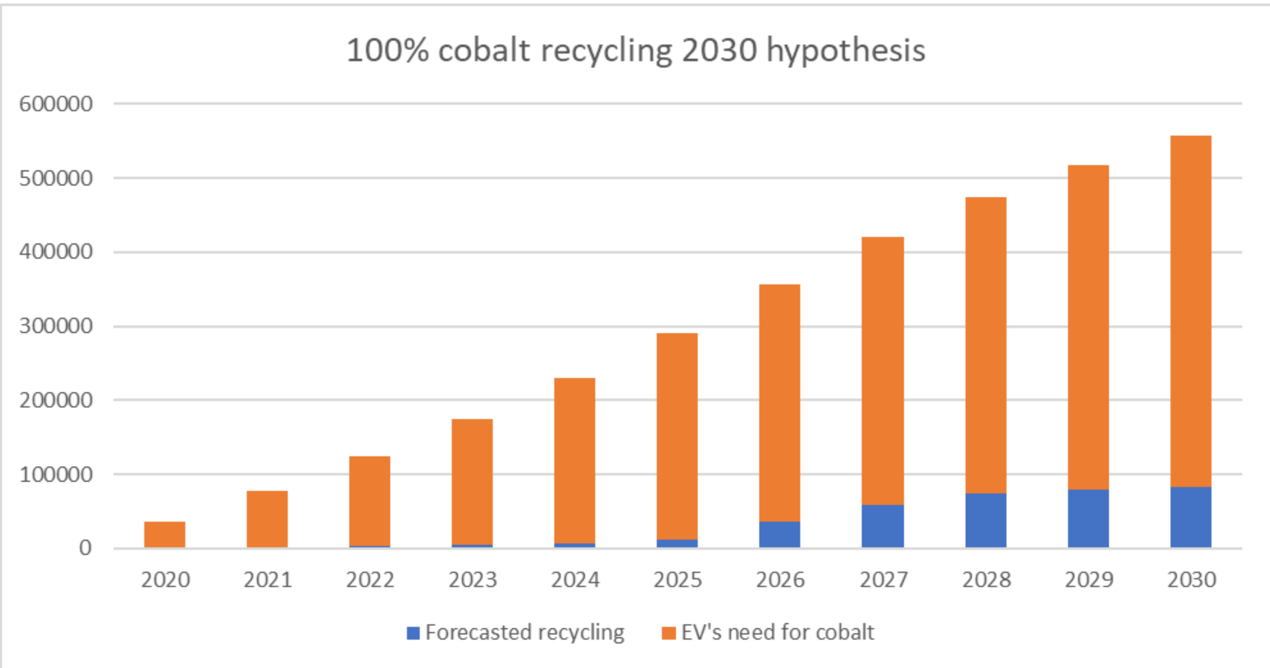


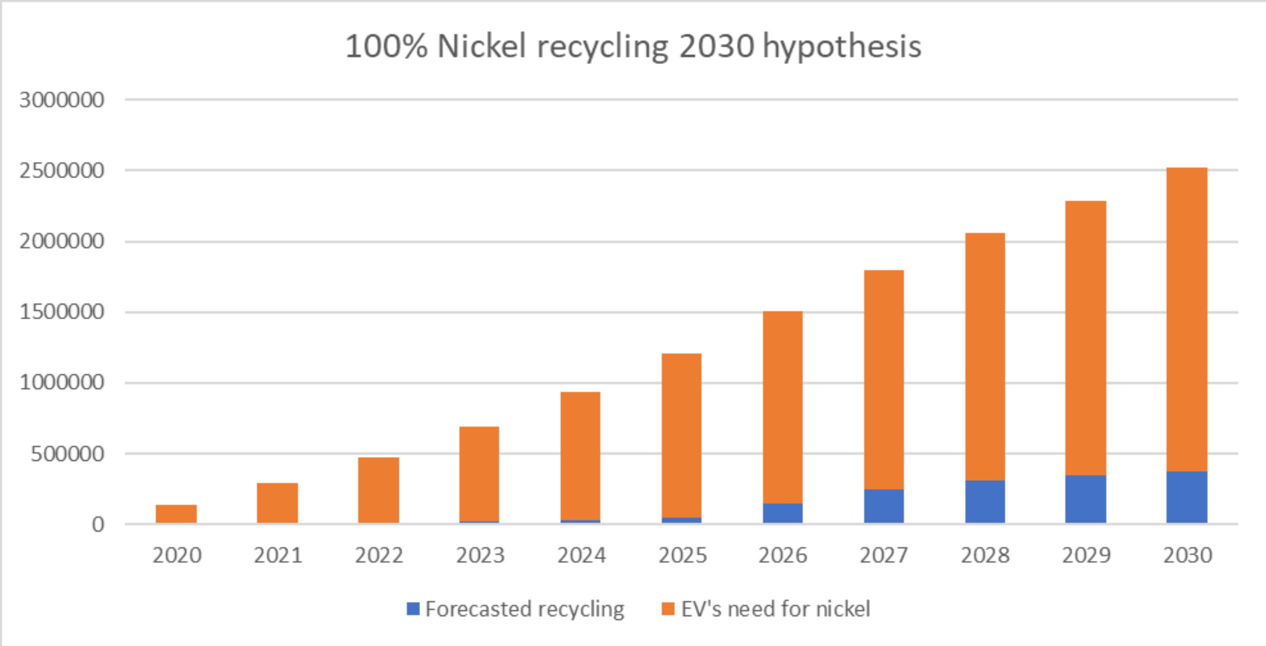


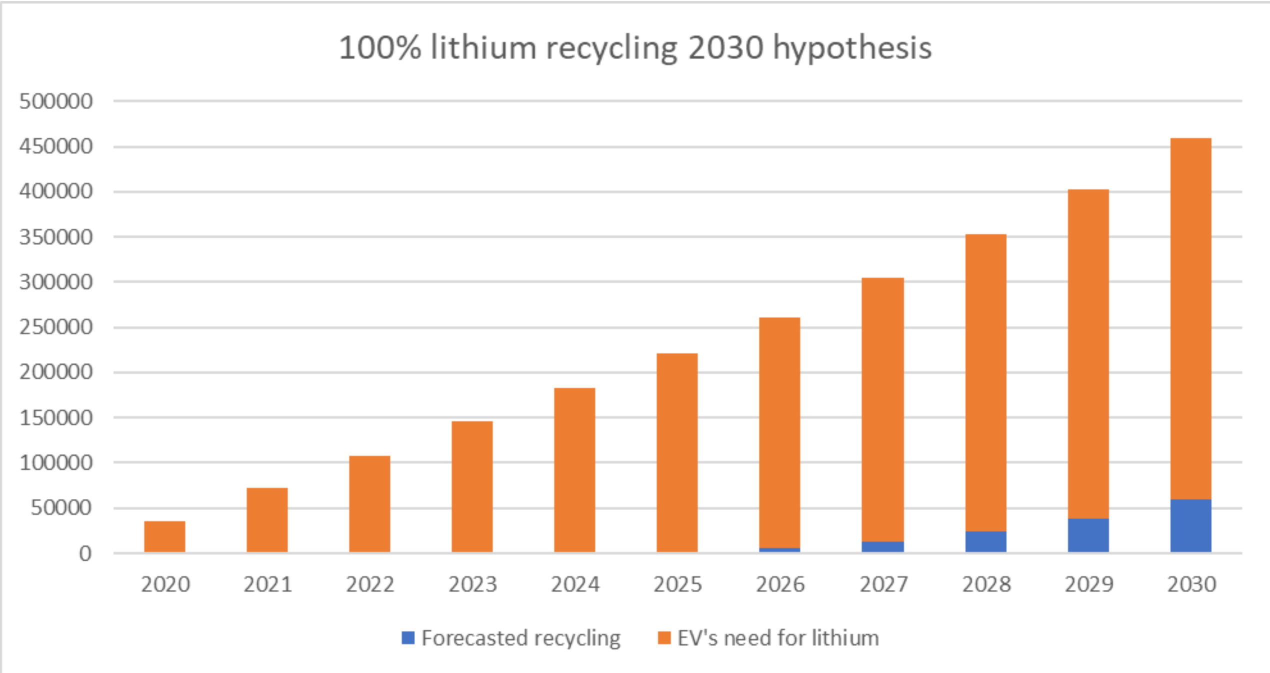


(Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

XVI. Share of rare materials recycling with 100% recycling 2030 hypothesis compared with EVs production.

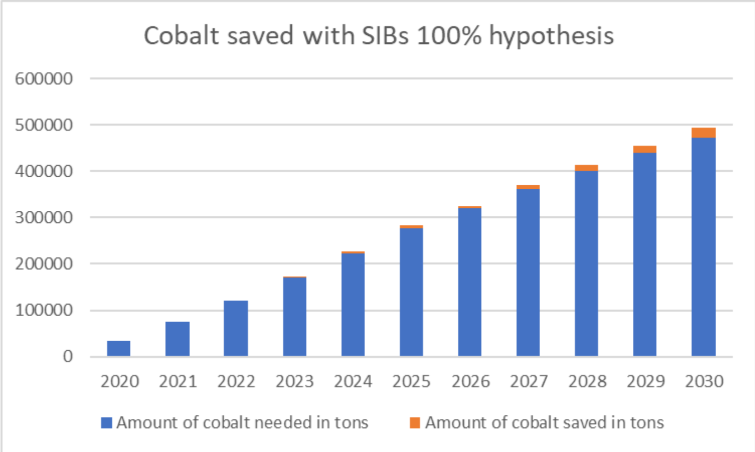


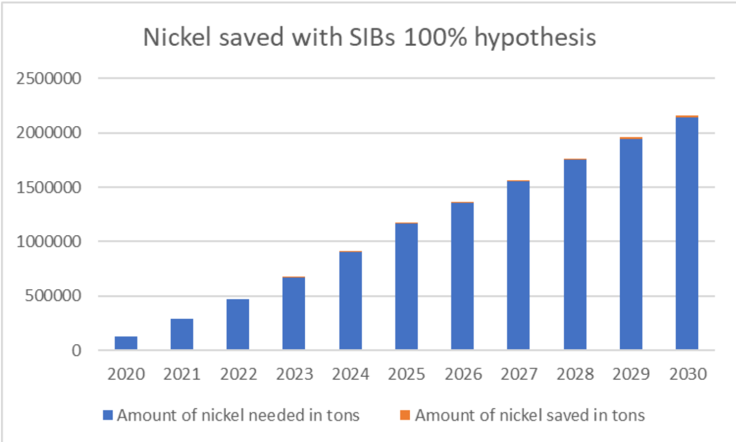


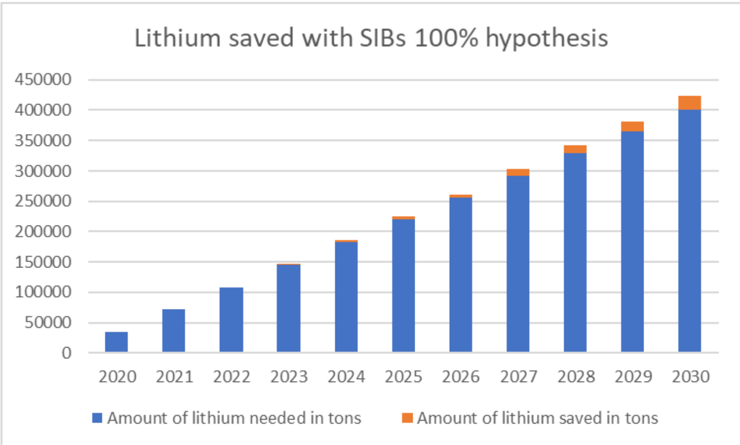


(Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

XVII. <u>Lithium, Cobalt & Nickel saving with 100% SIBs for stationary storage estimation comparison with materials needs.</u>

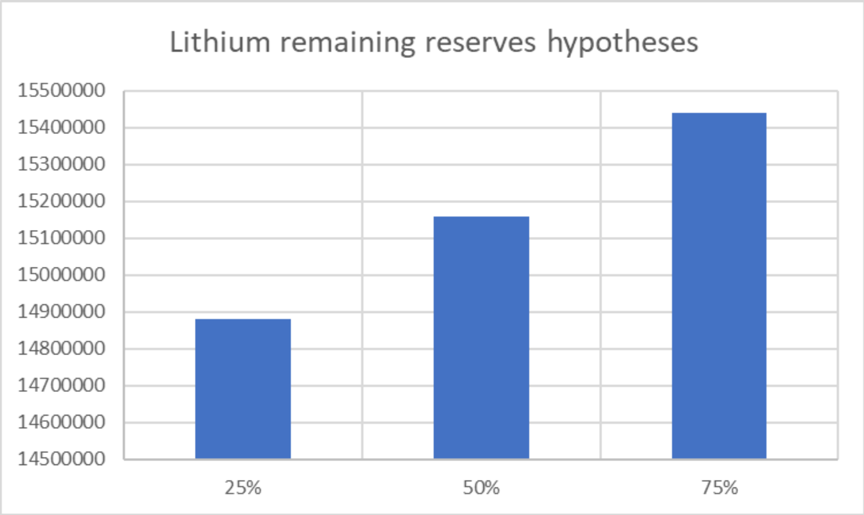


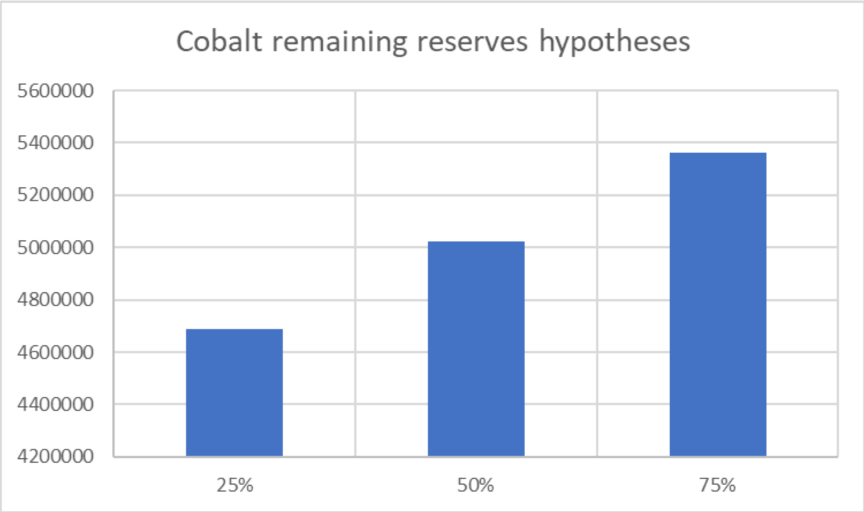


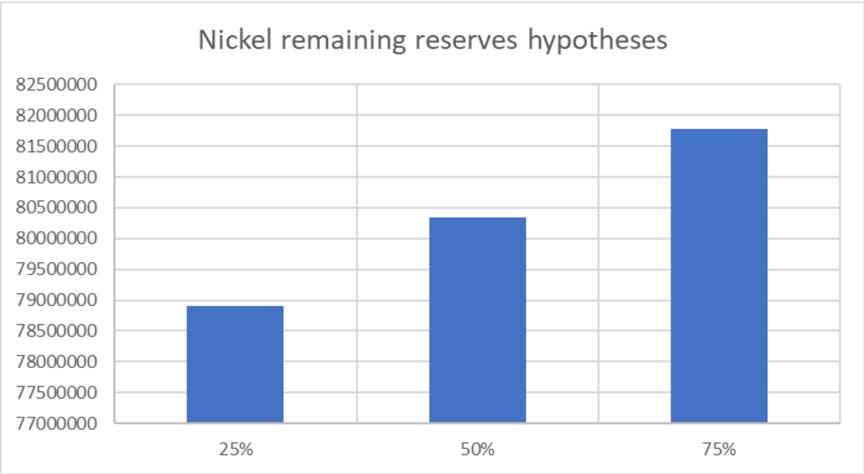


(Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a, 2021b ; Valero et al., 2018 ; Xu et al., 2020))

XVIII. Lithium, Cobalt & Nickel remaining reserves by hydrogen & zinc-air extender use impact on large & mid-size EVs market shares.



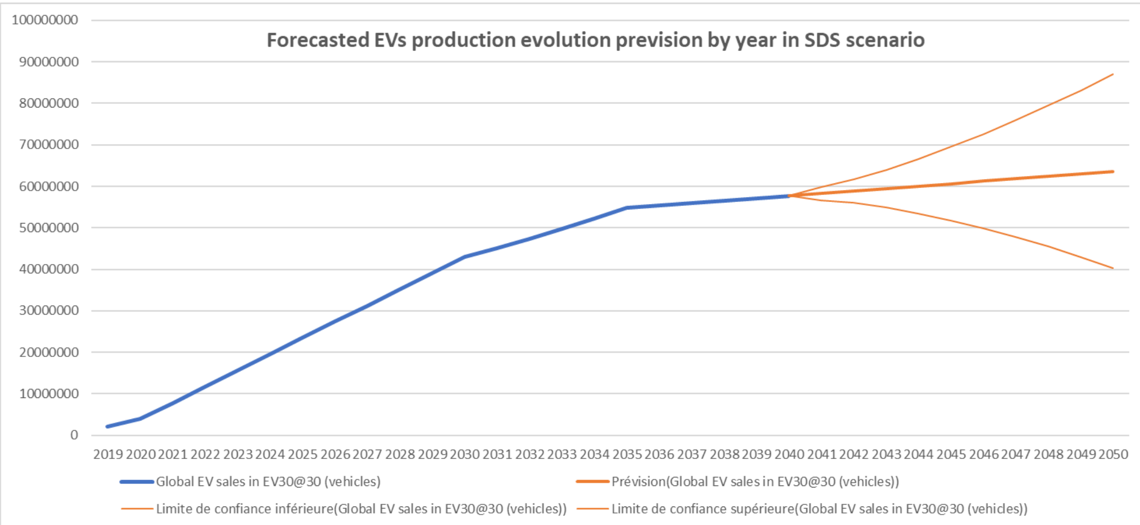




(Data sources: (Nguyen et al., 2021 ; Publications Office of the European Union, 2018 ; Statista, 2021a ; Valero et al., 2018 ; Xu et al., 2020))

XIX. Forecasted EVs evolution between 2040 & 2050, table & chart.

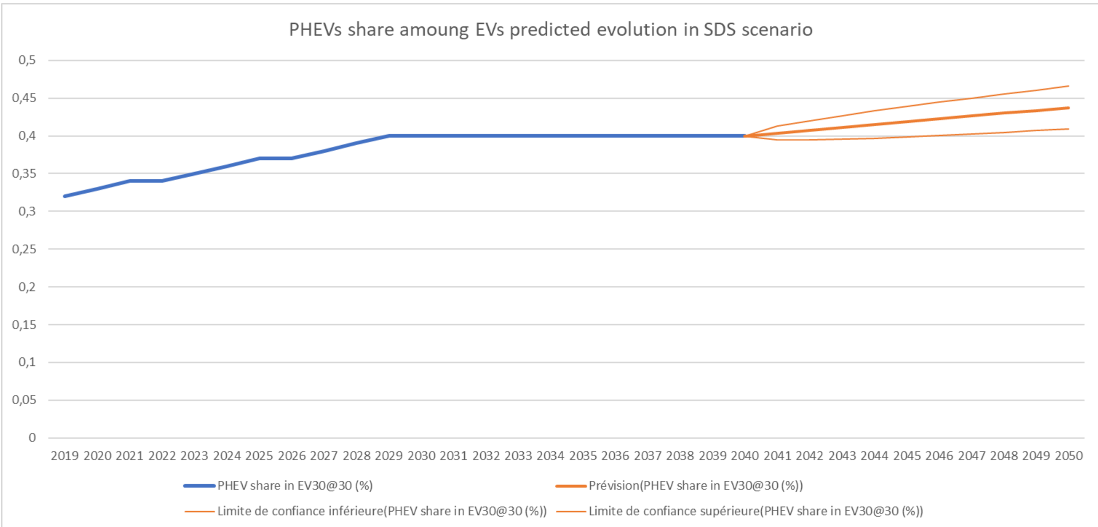
Year	Global EV sales in EV30@30 (vehicles)	Prévision(Global EV sales in EV30@30 (vehicles))	Limite de confiance inférieure(Global EV sales in EV3	Limite de confiance supérieure(Global EV sales in EV3
2019	2150000			
2020	3900000			
2021	7810000			
2022	11720000			
2023	15630000			
2024	19540000			
2025	23450000			
2026	27360000			
2027	31270000			
2028	35180000			
2029	39090000			
2030	43000000			
2031	45150000			
2032	47407500			
2033	49777875			
2034	52266769			
2035	54880107			
2036	55428908			
2037	55983197			
2038	56543029			
2039	57108460			
2040	57679544	57679544	57679544,00	57679544,00
2041		58243911,83	56659490,13	59828333,52
2042		58844142,98	55989104,34	61699181,63
2043		59444374,14	54879560,66	64009187,63
2044		60044605,3	53457808,92	66631401,68
2045		60644836,46	51778439,00	69511233,92
2046		61245067,62	49872489,24	72617646,00
2047		61845298,77	47760904,68	75929692,87
2048		62445529,93	45459255,40	79431804,47
2049		63045761,09	42979812,30	83111709,88
2050		63645992,25	40332623,62	86959360,88



(Data source : (Nguyen et al., 2021))

XX. <u>Forecasted PHEVs market share evolution between 2040 & 2050, table & chart.</u>

Year	PHEV share in EV30@30 (%)	Prévision(PHEV share in EV30@30 (%))	Limite de confiance inférieure(PHEV share in EV30@3	Limite de confiance supérieure(PHEV share in EV30@
2019	0,32			
2020	0,33			
2021	0,34			
2022	0,34			
2023	0,35			
2024	0,36			
2025	0,37			
2026	0,37			
2027	0,38			
2028	0,39			
2029	0,4			
2030	0,4			
2031	0,4			
2032	0,4			
2033	0,4			
2034	0,4			
2035	0,4			
2036	0,4			
2037	0,4			
2038	0,4			
2039	0,4			
2040	0,4	0,4	0,40	0,40
2041		0,40	0,39	0,41
2042		0,41	0,39	0,42
2043		0,41	0,40	0,43
2044		0,41	0,40	0,43
2045		0,42	0,40	0,44
2046		0,42	0,40	0,44
2047		0,43	0,40	0,45
2048		0,43	0,40	0,46
2049		0,43	0,41	0,46
2050		0,44	0,41	0,47



(Data source : (Nguyen et al., 2021))

XXI. Forecasted market share evolution between 2038 & 2050 of critical materials.

Chronologie	Co	Prévision(Co)	Limite de confiance inférieure(Co)	Limite de confiance supérieure(Co)
2020	18%			
2021	20%			
2022	22%			
2023	23%			
2024	25%			
2025	27%			
2026	28%			
2027	30%			
2028	31%			
2029	34%			
2030	39%			
2031	40%			
2032	41%			
2033	43%			
2034	46%			
2035	47%			
2036	47%			
2037	48%			
2038	48%	48%	48%	48%
2039		53%	51%	56%
2040		55%	52%	58%
2041		57%	54%	60%
2042		59%	56%	61%
2043		61%	58%	63%
2044		62%	60%	65%
2045		64%	62%	67%
2046		66%	64%	69%
2047		68%	65%	71%
2048		70%	67%	72%
2049		72%	69%	74%
2050		74%	71%	76%

Chronologie	Li	Prévision (Li)	Limite de confiance inférieure (Li)	Limite de confiance supérieure(Li)
2020	24%			
2021	26%			
2022	28%			
2023	30%			
2024	33%			
2025	35%			
2026	37%			
2027	39%			
2028	40%			
2029	45%			
2030	51%			
2031	52%			
2032	53%			
2033	56%			
2034	61%			
2035	61%			
2036	62%			
2037	63%			
2038	63%	63%	63%	63%
2039		70%	66%	73%
2040		72%	69%	76%
2041		75%	71%	78%
2042		77%	74%	80%
2043		79%	76%	83%
2044		82%	78%	85%
2045		84%	81%	88%
2046		87%	83%	90%
2047		89%	86%	93%
2048		92%	88%	95%
2049		94%	91%	97%
2050		96%	93%	100%

Chronologie	Ni	Prévision(Ni)	Limite de confiance inférieure(Ni)	Limite de confiance supérieure(Ni)
2020	3%			
2021	3%			
2022	3%			
2023	4%			
2024	4%			
2025	4%			
2026	5%			
2027	5%			
2028	5%			
2029	5%			
2030	6%			
2031	6%			
2032	7%			
2033	7%			
2034	7%			
2035	7%			
2036	8%			
2037	8%			
2038	8%	8%	8%	8%
2039		8%	8%	9%
2040		9%	8%	9%
2041		9%	9%	9%
2042		9%	9%	10%
2043		10%	9%	10%
2044		10%	10%	10%
2045		10%	10%	11%
2046		11%	10%	11%
2047		11%	10%	11%
2048		11%	11%	12%
2049		11%	11%	12%
2050		12%	11%	12%

(Data source: (Statista, 2021b))

XXII. Material usage predicted evolution in stationary.

Chronologie	Li	Prévision(Li)	Limite de confiance inférieure(Li)	Limite de confiance supérieure(Li)
2020	0,1			
2021	0,0925			
2022	0,07928571			
2023	0,09333333			
2024	0,08642336			
2025	0,07813665			
2026	0,04284211			
2027	0,05644068			
2028	0,05732394			
2029	0,05409357			
2030	0,05818182	0,058181818	0,06	0,06
2031		0,045179001	0,03	0,07
2032		0,040187908	0,02	0,06
2033		0,035196814	0,02	0,06
2034		0,030205721	0,01	0,05
2035		0,025214627	0,01	0,05
2036		0,020223534	0,00	0,04
2037		0,01523244	0,00	0,04
2038		0,010241347	-0,01	0,03
2039		0,005250253	-0,01	0,03
2040		0,00025916	-0,02	0,02
2041		-0,004731934	-0,02	0,02
2042		-0,009723027	-0,03	0,01
2043		-0,014714121	-0,03	0,01
2044		-0,019705214	-0,04	0,00
2045		-0,024696307	-0,04	0,00
2046		-0,029687401	-0,05	-0,01
2047		-0,034678494	-0,05	-0,01
2048		-0,039669588	-0,06	-0,02
2049		-0,044660681	-0,06	-0,02
2050		-0,049651775	-0,07	-0,03

Chronologie	Co	Prévision(Co)	Limite de confiance inférieure(Co)	Limite de confiance supérieure(Co)
2020	0,076283784			
2021	0,0705625			
2022	0,060482143			
2023	0,071198198			
2024	0,065927007			
2025	0,05960559			
2026	0,032681579			
2027	0,043055085			
2028	0,043728873			
2029	0,04126462			
2030	0,044383292	0,044383292	0,04	0,04
2031		0,034464251	0,02	0,05
2032		0,030656856	0,02	0,05
2033		0,026849462	0,01	0,04
2034		0,023042067	0,01	0,04
2035		0,019234672	0,00	0,03
2036		0,015427277	0,00	0,03
2037		0,011619882	0,00	0,03
2038		0,007812487	-0,01	0,02
2039		0,004005092	-0,01	0,02
2040		0,000197697	-0,02	0,02
2041		-0,003609698	-0,02	0,01
2042		-0,007417093	-0,02	0,01
2043		-0,011224488	-0,03	0,00
2044		-0,015031883	-0,03	0,00
2045		-0,018839278	-0,03	0,00
2046		-0,022646673	-0,04	-0,01
2047		-0,026454068	-0,04	-0,01
2048		-0,030261463	-0,05	-0,02
2049		-0,034068858	-0,05	-0,02
2050		-0,037876252	-0,05	-0,02

Chronologie	Ni	Prévision(Ni)	Limite de confiance inférieure(Ni)	Limite de confiance supérieure(Ni)
2020	0,01216216			
2021	0,01125			
2022	0,00964286			
2023	0,01135135			
2024	0,01051095			
2025	0,00950311			
2026	0,00521053			
2027	0,00686441			
2028	0,00697183			
2029	0,00657895			
2030	0,00707617	0,007076167	0,01	0,01
2031		0,005494743	0,00	0,01
2032		0,004887718	0,00	0,01
2033		0,004280694	0,00	0,01
2034		0,003673669	0,00	0,01
2035		0,003066644	0,00	0,01
2036		0,002459619	0,00	0,00
2037		0,001852594	0,00	0,00
2038		0,001245569	0,00	0,00
2039		0,000638544	0,00	0,00
2040		3,15194E-05	0,00	0,00
2041		-0,000575505	0,00	0,00
2042		-0,00118253	0,00	0,00
2043		-0,001789555	0,00	0,00
2044		-0,00239658	0,00	0,00
2045		-0,003003605	-0,01	0,00
2046		-0,00361063	-0,01	0,00
2047		-0,004217655	-0,01	0,00
2048		-0,00482468	-0,01	0,00
2049		-0,005431704	-0,01	0,00
2050		-0,006038729	-0,01	0,00

(Data source: (Statista, 2021b))

Executive summary

The society is facing multiple worrying problems. Among those, one particularly complex issue is the global warming due to greenhouse gases emissions. In 2016, the transportation sector was responsible for 16.2% of those emissions. The same year, 11.9% of global greenhouse gases emissions came from road transport only (Ritchie & Roser, 2020).

Nowadays, main solution proposed to reduce those emissions consists in transitioning to electric road transport. However, governments and citizens have multiple concerns about electric vehicles. Two of those are tackled in this thesis: The pollution of electric vehicles compared to fossil fueled vehicles & the scarcity and risk of shortage of components needed to produce electric vehicles.

About the first concern, it is proven that electric vehicles do emit less than fossil fueled vehicles. Indeed, considering their whole lifecycle, regardless of the country, electric vehicles always emit less greenhouse gases (International Council on Clean Transportation Europe & Georg Bieker, 2021). However, for what concerns materials' possible scarcity, the problem is more complex.

The purpose of this thesis is to tackle this potential problem. Firstly, most critical materials present in electric vehicles batteries were identified. Then, an evaluation of the required quantities for estimated and potential growths in those vehicles production was realized. Most critical materials were identified regarding their potential depletion. Those materials are Lithium, Cobalt & Nickel.

After that, impact of recycling was investigated. This highlighted one fact: recycling of lithium is currently low despite the existence of efficient techniques to recover almost 100% of those materials (Chan et al., 2021). However, Cobalt & Nickel have already high recovery rates with disposed batteries (Mossali et al., 2020).

This thesis then investigates possible substitutes & complements for electric vehicles. Sodium-ion batteries have promising characteristics. In stationary storage sector, they work as well as numerous lithium-ion batteries (Abraham, 2020). For electric vehicles application however, sodium-ion batteries have not the performance needed yet (Zhang et al., 2019).

Possible extensions for electric vehicles' batteries were also investigated. Hydrogen fuel cells & Zinc-air battery packs are possible extenders (Wu et al., 2019), (Tran et al., 2020). They present numerous advantages, and in particular leverage reduction in size of batteries as they increase electric vehicles' range. This need's reduction for bigger batteries results in a demand's reduction for rare materials.

Considering all these tools, the thesis investigates possible materials' scarcity according to the most ambitious scenario of electric vehicles' production (International Energy Agency, 2020). This assessment was made with actual recycling rates & their predicted evolution. It is to note that only actual battery chemistries already on road were considered.

Without the use of the aforementioned technologies, results of this analysis for 2030 shows an important materials' depletion. On the horizon of 2050, Cobalt reserves would be depleted. Analyzing global materials market, lithium & nickel would also be too scarce.

However, using intensively aforementioned technologies changes the results. Additional worldwide efforts on recycling with intensive usage of hydrogen zinc air extenders save rare resources. Sodium-ion batteries could also be indirectly useful. Those could decrease rare materials' needs in stationary applications. Thus, using the good technologies, most of vehicles could be electric by 2050 without depleting rare materials' reserves. This would mean near zero emissions by 2050 for road transport.

Keywords: Electric, Vehicle, Material, Battery, Scarcity, Recycling, Chemistry, Extender, Depletion, Evolution

Word count = 12,621