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Environmental aspects of Electric mobility:
The case study on Copper

Bachelor Thesis

by

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Statutory Declaration

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ENVIRONMENTAL ASPECTS OF ELECTRIC MOBILITY:
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independently and without undue external help. I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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PREFACE

First of all, it is necessary to state that this thesis would be one part of the one joined study, and some specific parts of this work can be identified with another study's analysis.

Another thesis topic is " Resource Management in Electric mobility: Case Study on Copper," which is done by senior industrial engineering student Zayabolor. It mainly focused on the market outlook of electric vehicles (EVs) and copper (Cu) and estimated the share of the copper demand, which is solely due to the EVs demand surge in the long term.

On the other hand, this work concentrated on the environmental impacts concerning EVs and life-cycle copper production and aims to estimate which fraction of the environmental footprint of Cu production is only due to the increase in EVs demand in the future.

For these reasons, some analysis and data in this work can be dependent on the output of another’s study.

ABSTRACT

The current state of climate change and global warming calls for immediate action from any industry that can show a considerable benefit for it, especially the electric mobility industry, which can erase the pollution caused by internal combustion engine industries. However, it can be vary depending on several factors, including electricity source, a variation of an electric propulsion system of EVs, material footprint, and geographical region. Reliable research about far-reaching environmental impacts only due to the electromobility is of utmost importance. Copper is one of the priority elements that are essential to electromobility technology. While copper is used throughout electric vehicles, charging stations, and supporting infrastructure because of the metal's durability, high conductivity, and efficiency, it has a tremendous impact on the environment regarding CO2 loading.

In this study, the ways of dealing with the environmental aspect of electromobility concerning copper are discussed. First of all, the changes in the copper demand due to the drastic growth of the electric vehicle is estimated. Furthermore, which fraction of the environmental footprints generated from a copper production is consumed in the EV industry alone is estimated.

Consequently, the study shows that the global copper supply market and world copper will meet this demand for up to 200 years, although copper consumption will increase as demand for EVs intensifies. One of the major solutions to reduce the environmental footprints of copper production is to support and fund copper recycling through government policies.

As a result, it concluded that copper demand, which is caused due to EVs, would reach 3,494Mt out of 47, 094Mt by 2035. This is accounted for 7,42% of the total copper demand in 2035. There are no issues that will arise because of electric vehicles unless specific supply chain problems occur due to economic aspects such as lack of smelter capacity of copper. However, the electric vehicle field can have a massive impact on the production and resource of some particular raw materials, in the copper world.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

1.1 General information

1.1.1 Electromobility

Electric mobility comprises all street vehicles that are powered by an electric motor and primarily get their energy from the power grid. This includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), range-extended electric vehicles (REEVs). If electric groups are grouped in another way, it includes passenger light-duty vehicles (PLDVs), light commercial vehicles (LCVs), buses, trucks, two/three-wheelers. Aside from electric cars, the whole concepts, including the energy supply issues as well as the charging and traffic infrastructure, must be covered, since all sectors are interconnected together. EVs were first invented in the mid 19-th century; however, the rise of internal combustion engines contributed to the decline of electric cars and led to its reintroduction in the last few decades as the environmental impact of a vehicle became high in priority (34).

The electric mobility concept is gaining power drastically in the automotive industry. According to the report done by BloombergNEF, over 2million electric vehicles were sold in 2018 compared to a few thousand in 2010, showing the implication that the number will get much more prominent in the future (32). The same report states that by 2040, 57% of all passenger vehicle sales and over 30% of the global passenger sales will be electric. More findings will be introduced in the main report discussion.

1.1.2 Raw materials in electromobility

In comparison to conventional vehicles, electric vehicles require a much higher amount of technology metals in their propulsion systems. Key components of electric vehicles are traction batteries, electric motors, and power electronics, and each of them relies on different kinds of metal, respectively. Whereas the motors are in need of rare earth, several specific materials, in particular, lithium and cobalt, are essential in electric car batteries. In power electronics, copper, and precious metals such as gold, silver, and palladium play an essential role. Besides, light-weight materials are essential in vehicle construction as well, including aluminum and carbon fiber-reinforced polymer. (1)

In terms of the situation concerning their demand and availability, undoubtedly, lithium attracts the most attention in the electric vehicle field due to its high demand. This list is followed by cobalt. Apart from lithium and cobalt, there are sufficient resources available to meet the growing demand for technology metals in the medium and long term. (1)

However, from the ecological and economic perspective, inevitable consequences will arise due to the supply for these drastically increasing demands. It shows that secondary material usage from recycling and innovative technologies that reduce specific and absolute resource demand is strategically significant in the electric mobility field in the future. While the recycling of the rare earth is questionable in electric motors, lithium, cobalt, and nickel are the main focus. In power electronics, copper and precious metals also should be considered similarly.

Substitution can also be an alternative solution for scarce resources and other arising issues. Substitution means replacing the raw materials with other materials with similar properties but is either economical or ecologically beneficial.

For example, neodymium-iron-boron permanent magnet motors can be replaced by asynchronous motors, which are rare earth-free. (1)

1.1.3 Copper

Copper is a reddish-gold metal by the appearance that is accounted for by its properties of ductility, malleability, and machinability. Historically it has been one of the metals used to make coins, along with silver and gold. However, copper is relatively affordable than the other two. According to the study (35), most copper is used in electrical equipment such as wiring and motors, and the EV industry takes advantage of this feature. It also has uses in construction (for example, roofing and plumbing), and industrial machinery (such as heat exchangers). Copper metal does occur naturally, but by far the greatest source is in minerals such as chalcopyrite and bornite. (2) Copper is obtained from these ores and minerals by subsequent processes, namely are extraction, concentration, smelting, and refining.

As a general guiding principle, however, it is evident that the closer that an EV becomes to replicating the performance of ICE, the more copper content it will require to do so. Therefore, the larger the vehicle the greater the amount of copper will be used. This is because copper is an essential element to an electric vehicle’s motor, battery, power electronics as well as the infrastructure, which includes charging infrastructure and possible update on the current power grid.

1.2 Problem statement

- Most of the specified studies regarding the primary raw materials, in particular, copper, which is of utmost importance to assemble the electric mobilities, did not take into account abrupt changes in demand for an electric vehicle when they estimate future copper demand. It is questionable whether it is inevitable that there will not be enough copper or, worse, that it may run out for an electric mobility surge in the long-term.
- There is a lack of clearly identified studies of the environmental impact of an increase in copper demand and production due to the growth of electric vehicles.
- There is a need for an evaluation which states whether there is a difference between the environmental footprint of Cu production due to only EVs and the environmental footprint of Cu for other purposes.
- There are few studies on the copper recyclability from EVs and environmental benefits or consequences of second source copper production.

1.3 The objectives of the study

- To find out about the cruciality of copper in electric mobility to strive and assess the possibility that other elements can eventually replace its function throughout the evaluation of electric mobility in the future.
- To specify copper production required in the EV industry and to estimate the change in copper demand due to the electric mobility industry.
- To assess the environmental aspects of EVs growth in general and to analyze environmental footprint only regarding the change in copper demand due to the demand surge in the EV industry based on previous data.
- To assess whether there is a difference between the environmental footprint of Cu production due to only EVs and the environmental footprint of Cu for other purposes.
- To study copper recycling availability from the EVs and its benefit on environmental footprint.

2 Electric vehicles and its environmental impacts

2.1 Market Outlook

The rapid growth in EV sales and fleets is one area where world electricity consumption will begin to accelerate. In 2017 global EV sales reached 1.1 million units, a 54% year-on-year increase, although only 2.2% of all new auto registrations. In 2018, this number exceeded two million, there is no sign of slowing down (33). The report expects annual passenger EV sales to rise to 10 million in 2025, 28 million in 2030 and 56 million by 2040. Based on this data, the global EVs share of annual passenger vehicle sales is expected to exceed the ICE annual sale shares by 2040 (32). (see Figure 1.)

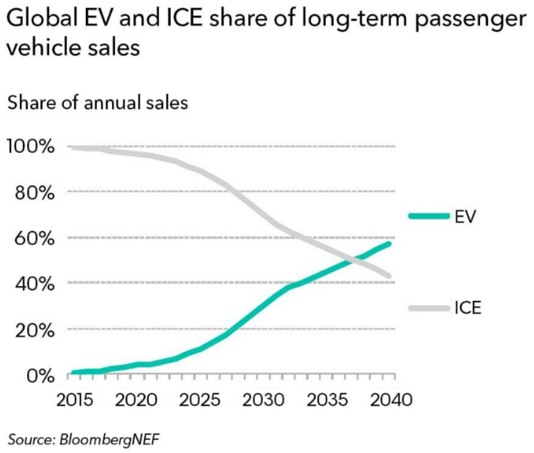


Figure 1: Global EV and ICE share of long-term passenger vehicle sales. Adapted from (32)

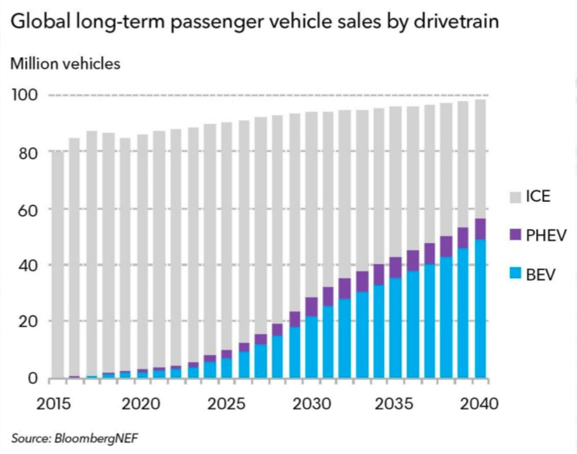


Figure 2: Global long-term passenger vehicle sales by drivetrain. Adapted from (32)

If we take a closer look at these shares by EVs type, BEV accounts for the majority of the EVs sales consistently. (see Figure 2.) The study (3) state that BEV play a key role in future mobility scenarios.

2.2 Environmental impacts of EVs

In figure 3, the simplified flow chart of the life cycle of EVs is shown. As discussed above, some phases show positive results, while others indicate an adverse impact. However, regardless of whether the result is beneficial or damaging to the environment, all phases of the life cycle of EVs must be involved to analyze overall environmental impacts, which is due to EVs' growth.

Due to the BEVs domination in the EVs market, environmental impacts of the production, use, and disposal of the lithium-ion (Li-ion) battery should be in the spotlight to compare the environmental impacts of EVs with those of internal combustion engine cars (ICEVs) (3).

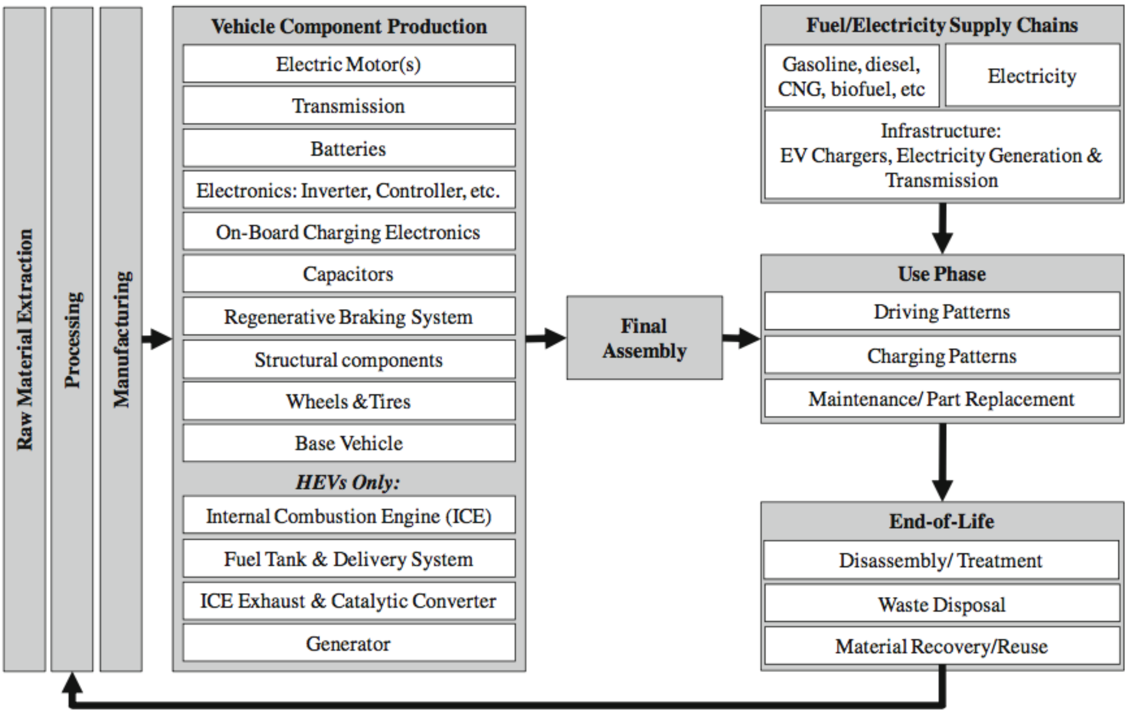


Figure 3: Simplified flow chart of the life cycle of EVs. Adapted from (9).

It is evident that as EVs gain power in the automotive industry, the demand for some specific raw material will increase in parallel. According to Burak et al., as cited by the U.S. Department of Energy (DOE) (4), anticipated further development of EVs will result in a dramatic increase in the demand for some raw materials, including copper, nickel, aluminum, and steel. As emphasized by Copper Development Association Inc. (5) , the copper market will significantly affect by electric vehicles breakthrough, and the demand for copper due to EVs is expected to increase by 1,700 kilotons by 2027. Simultaneously, graphite, nickel, aluminum, cobalt, lithium, and manganese market are forecast to be faced with demand surge due to EVs. (see Figure 4)

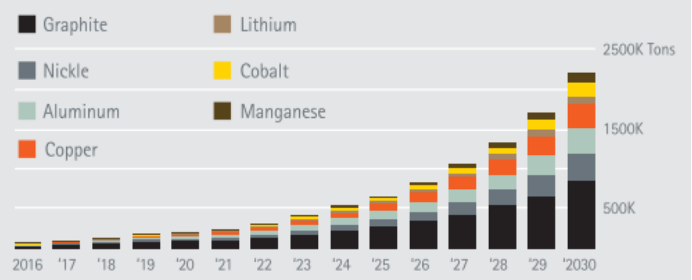


Figure 4: Demand surge for some raw materials due to EVs. Adapted from (4)

Therefore, the raw material extraction, production, and manufacturing phases of EVs life cycle would negatively impact the environment caused by EVs growth. Firstly, it is necessary to study changes in material footprint and environmental impacts of the production, use and disposal of the materials and components.

On the other hand, by replacing internal combustion engine vehicles, the benefit that electric vehicles could bring to the rising concern of climate change is evident. There are several studies (6-8) that show how the use of EVs can contribute to the fight against global warming and climate change by comparing the environmental footprints caused by ICEVs with those of EVs such as energy consumption, carbon footprint, water footprint, air pollutant emission. In most cases, this kind of study usually results in that environmental impacts are higher for ICEVs than those of EVs by conducting life-cycle environmental and/or economic assessments. Therefore, the environmental benefits by EVs are determined mostly at the use/operation phase.

For the EoL phase, it has the potential to lead both negative and positive results, because it is significantly affected by the use of innovative technology, recycling policies, and regulation.

However, as it is typical for methodologies and assumptions to be different, the results of the studies differ in a wide range from one factor to another factor.

For instance, electricity source or electricity grid mix assumption has a significant influence on the CF estimation of EVs.

This makes it quite challenging to estimate environmental footprints due to EVs industry overall and to compare them with those of ICEVs.

As mentioned by study (8), ‘ definition of vehicles considered makes comparison across studies difficult.’ (p.1003).

You can see further some detailed analysis of both positive and negative environmental impacts due to EVs from the following subchapters.

2.2.1 Adverse impact on environment due to raw material and component production for EVs

The use of EVs is indeed much more beneficial than ICE to the environment from energy consumption, carbon footprint, water footprint, or air pollutant emission perspectives. However, at the same time EVs bring up some other issues regarding material footprint (MF), increase in GWP due to raw material production and vehicle manufacturing. (see Figure 3.)

Material Footprint: As defined by Lutter et al. (9), 'the MF illustrates the amount of materials required for specific products along their entire supply chains from raw material extraction to final demand' (p.2). Although many studies have been estimated in Footprint Family, which is solely due to EVs, there are only a few pieces of literature that applied LCA for estimating MFs of EVs at the product level.

One of the available studies is Burak et al. (4). In order to analyze the materiality aspect of emerging EVs and compare MFs of ICEV, and BEV, the researchers dealt with global life cycle material footprints in particular of 10 metals (copper, lead, nickel, tin, zinc, uranium and thorium, precious metal, ores of iron, bauxite, and aluminum, and other metals) by using an MRIO-based life cycle assessment method based on the EXIOBASE 2 database.

From Figure 5, you will see the result of the study (4).

The life-cycle material footprint of BEVs is much higher than ICEV's LCMF. Quantitatively, the LCMFs of ICEV and BEV is around 16, and 42 tons per vehicle, respectively, which means BEV's LCMF is 60% higher than ICEV's total MF. This ratio is the same for each life cycle phase, namely, manufacturing, operation, and end-of-use (4).

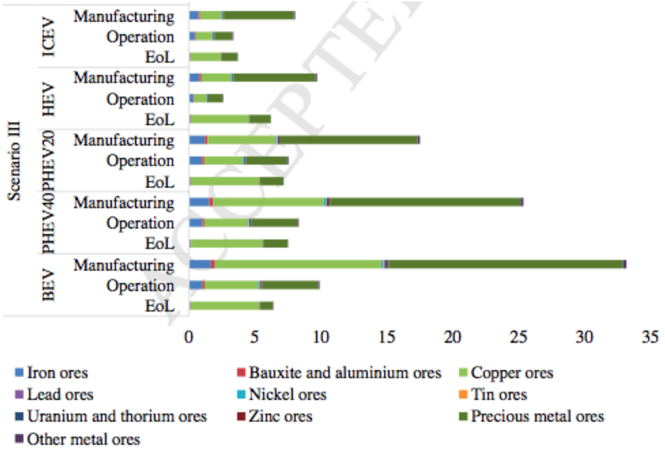


Figure 5: Material footprints for different life cycle phases by the amount of metals (tons). Adapted from (4)

The interesting thing is that the manufacturing phase was not only the most responsible phase among all lice-cycle phases in all types of vehicles studied but also the stage that significantly differentiates MF between ICEVs and EVs. As described by Burak et al. (4), it is due primarily to the manufacturing of batteries.

Here, the manufacturing phase comprises of material extraction, procurement, and production. In contrast, the operation phase encompasses petroleum supply for conventional vehicles, electricity generation, transmission and distribution for EVs, and maintenance and repair (M&R) activities. The EoL deals with the disposal management of vehicles, which is divided into the reprocessing of metals, and landfill and incineration of plastics used in a vehicle.

Global warming potential: From the previous study’s result, the idea will come up that we should pay more attention to the environmental impacts of battery production. MF for battery production can be differ depending on some factors such as lifetime, its type, and energy efficiency.

As emphasized by Hawkins et al. (8), it is common for estimating GWP of battery production to measure with gCO2e per kilometer. In many studies, it is verified that target GWP is considerably affected by the battery lifetime, and battery lifetime is assumed to be between 150,000 - 300,000 km. Although battery lifetime is shorter than vehicle lifetime in most case and batteries are usually assumed to be replaced once during the operation phase of each EVs, there is some exceptions.

For instance, the lifetime of the NiMH battery used in Toyota Prius is estimated to be 240,000 km which is longer than the expected lifetime of the Prius itself.

As concluded by Hawkins et al. (8) ICEVs tend to have the lowest production-related GWP followed by HEVs, then PHEVs, and finally BEVs reflecting, which reflects the increased GWP associated with battery production.

The production of the battery emits considerable amounts of PM10, NOx, and SO2. (3)

According to Dominic et al. (3), the major contributor to the battery's environmental burden is the supply of copper and aluminum for the production of the anode and the cathode, plus the required cables or the battery management system. (p.6550).

2.2.2 Environmental gains due to EVs

In recent years, integrated footprint analysis is receiving a lot of attention from not only scientists but also governments as the planet's ecological degradation calls for immediate action from decision-makers around the world and integrated approaches has potential to enable addressing multiple issues at once and help avoid additional costs and make progress in one sector which face some issue by ignoring the direct and indirect effects of other sectors (10). Galli et al. (10) provided the term “Footprint Family” for the first time, which can define all approaches in the integrated ecosystem analysis, including CF, WF, energy use, and GWP.

To estimate actual environmental benefits which come up with EVs growth, all members of the family should be analyzed, especially in both phases of its life cycle, usually compared with those of ICEVs. Probably for those reasons, the majority of the studies conduct LCA or LCI to estimate the desired value, and it usually includes manufacturing, operation, and EoL phases (4). However, indicators overlap, interact, and complement should be considered and defined accurately at the same time because similarities and differences among the indicators can occur (10).

Carbon footprint: CO2 and GWP are the most frequently reported results (8).

As concluded by the study(11) , current CF indicators for EVs and conventional gasoline In the Czech Republic are 21.53 kg CO2 eq/100 km and 34.23 kg CO2 eq/100 km, respectively. Here, the required electricity is assumed to come from the current combined grid (Nuclear 40%, Lignite 30%, Hard coal 10%, and others).) When they anticipate this comparison as of 2050 by assuming their around 70% of electricity comes from Nuclear, CF indicators for EVs is reduced into 13.42 g CO2 eq/100 km.

It indicated CF's dependency on electricity sources. Although EVs appear to demonstrate decreases in GWP compared to conventional ICEVs, high-efficiency ICEVs and grid-independent hybrid electric vehicles perform better than EVs using coal-fired electricity. (1) EV results in regions dependant on coal electricity demonstrated a trend toward increased SOx emissions compared to fuel use by ICEVs. (8)

A study by BloombergNEF (32) says that despite the rapid uptake of electric vehicles across many different vehicle segments, direct CO2 emissions from road transport continue rising for the next ten years before peaking in 2030, mainly due to a growing internal combustion vehicle fleet. If additional power sector emissions from generation are added, the peak is 2-3 years later. By 2040, direct emissions from passenger cars, commercial vehicles and buses have returned to similar levels as in 2018 (32). If national governments want to hit the aggressive emissions reductions targets they have set, a stronger policy push will be needed to accelerate adoption.

2.2.3 Other issues regarding EVs

Not only great environmental consequences but also socio-economic impacts are likely to arise due to the anticipated growth in electric vehicles.(4)

The problems related to electromobility are mainly related to its lack of sales and low popularity. Tracking down the specific reasons behind it, it can be concluded that the essential cause lies in the socio-political field. A study (31) states some of the difficulties that come with implementing such an idea. The public, in other words, consumers, will have to change their preference for private car owners. As the paper states, this will be quite difficult due to several reasons: financial considerations being the dominant reason for not switching their current vehicle type. Another difficulty that arises with the idea is stated as "visions of the future of automobility are, and must be understood, as profoundly political and as conditioned by prevailing power structures (31) . We nonetheless observe a paradox: visions of simple technological substitution do not play to the strengths of EVs and – often unintentionally – perpetuate ownership and use of ICEVs as the norm against any other form of mobility has competed."

Another study (29) pays particular attention to issues of power and states that it might be the biggest hurdle to transition to electric vehicles for China. The paper tried to present the "power relational perspective at work in an insightful analysis of the case of Chinese urban e-mobility innovation". Stating its overall result as disappointing in terms of mass adoption and continues to suggest that the focus should stay on the issue of power/ knowledge reshaping and by introducing new paths of socio-technical and politico-cultural change, the results would probably show an improvement in the mass adoption of e-vehicles.

One of the improvements electric vehicles could bring to urban cities if noise reduction, says (34). Considering that the percentage of the population in cities will increase from 50% to 70%, the paper implemented empirical research in Berlin, which showed up positively. The paper states that consumers in the cities have good user acceptance of e-vehicles and neighbors were giving positive feedback.

3 The copper significance in EV industry

3.1 Copper use for EVs

This chapter explains in detail how copper drives EVs, and copper plays an essential role in which components of EVs. Furthermore, which type of Cu products (Cathode, Anode, or Blister) is specifically required and how EV manufacturers source their Cu for their products will be identified.

Although copper is considered as an integral part of the EVs, drastic change regarding design and material can be expected over the next decade. According to the forecast of a study (12), new vehicle designs and new components such as electric heaters will be introduced in the market soon. In particular, the general trend of lightweight construction is expected to gain strength in this field and might change the use of copper in the current EVs. (12)

Therefore, it is essential to consider material trends and its component's revolution based on the current rising requirements for EVs development to estimate the anticipated increase in copper demand due to EVs. Recently, Tesla introduced new battery tech in Emtech, and they emphasized the following characteristics as the most significant features for EVs further development:

- **A high density of energy, Excellent longevity, Wide temperature tolerance, Lightweight, Fast recharging time, Long-range, and Reasonable cost.**

According to the latest reliable sources (5), compared to the 20-25kg of copper in internal combustion engines (ICEs), hybrid electric vehicles (HEVs) might have double (~40kg) the copper intensity, plug-in hybrid electric vehicles (PHEVs) up to triple (~60kg) the intensity and battery electric vehicles (BEVs) up to four times (~83kg) the copper intensity. E-bus might use anywhere between 205kg (if it were a Hybrid) or 370kg (if it were purely battery-driven).

Many industrial sectors, including automotive, aerospace, construction, electricity, energy, electronics, and mechanical engineering, rely on copper due to its unique physical, chemical, thermal, electrical, and isolating properties (13).

In this field, copper is considered as the heart and veins for EVs, and it conquers EV manufacturers mostly by the following features(14):

- Conductivity: The first essential criterion for EVs industry is material conductivity. Copper has a conductivity of 5.98*10^7s/m. However, that is higher than gold but less than silver.
- Ductility: Its ductility is not good as gold or silver, but acceptable.
- Affordable: Undoubtedly, being profitable is the most important attribute for any business market. Copper costs 0.2$ per ounce, whereas silver is 15$ and gold is 1200$.

The main components of EV that employ copper are the electric motor, traction battery, and power electronics.(12) Apart from those key components, copper is considered as the most crucial material for providing EVs with infrastructure, including electricity grids and charging stations.

3.1.1 Traction batteries

It's known that the price of EVs mainly depends on the price of the battery it is powered by (30). In any type of electric vehicle, traction batteries are considered as the propulsion component. Although several types of batteries are being used in a wide range of design depending on their use in HEVs, PHEVs or EVs, almost exclusively either of the nickel-metal hydride (NiMH) or LIB typers are installed in today’s (H)EVs. (12) There are huge differences between HEV and other EV's battery types regarding its different requirements. For instance, whereas LIB’s energy efficiency of storage reaches 90 %, those of NiMH is lowest at 70 %. (8) Furthermore, NiMH batteries are mainly used in HEVs because NiMH performs relatively low specific energy of 80 Wh/kg, whereas LIB is preferred for PHEVs and Evs. (12)

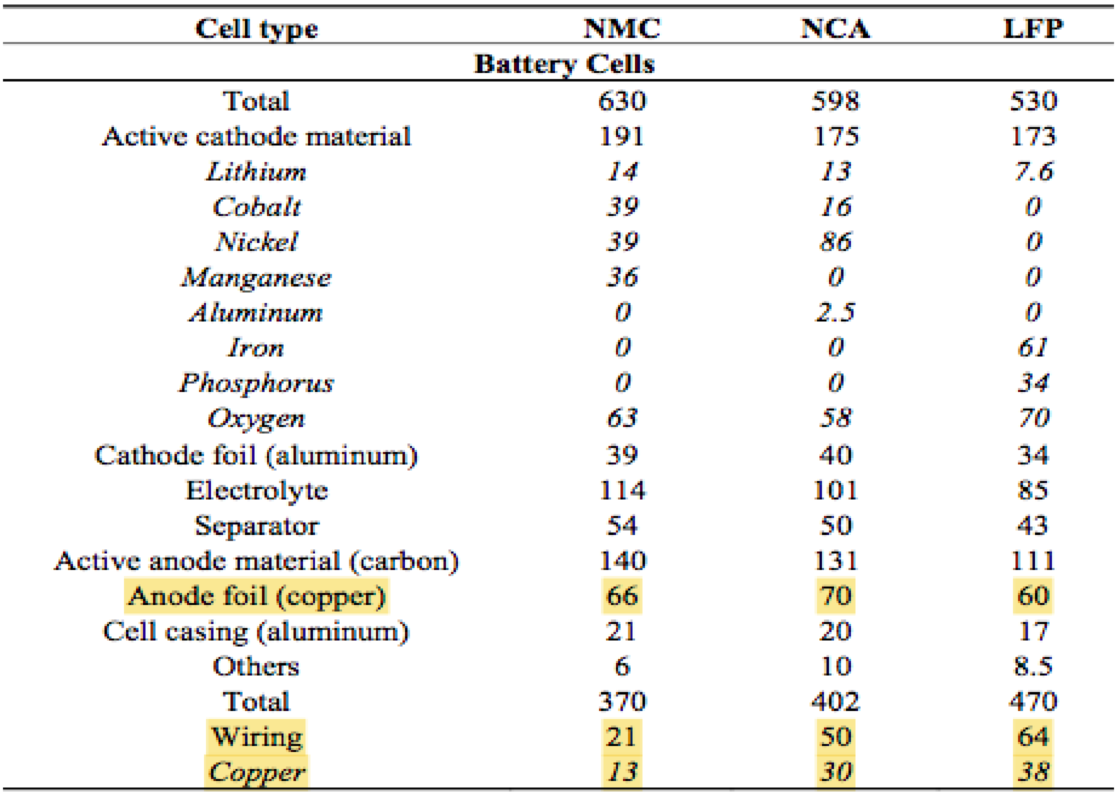
In other words, as LIB meets the requirement for EVs further development best due to its major attributes including its light-weight and its the impressive electrochemical potential which directly leads to the high power and energy density, it tends to continue to receive a lot of attentions in EVs market (3,11)

In this section, I will focus on the use of copper in LIB as defined in the scope of this study.

In the market, LIB with various type cathode material is available and among them LiMn2O4 is becoming trend in LIB industry due to its reasonable cost and better availability of manganese (3). Copper's main participation in LIB manufacturing occurs in anode production as anode is required to be coated by copper collector foil to intercalate Li-ions reversibly. In contrast, cathode is required to be coated by aluminum collector foil. However, as emphasized by Elwert et al.(11), as high operation voltage would be the aim of future battery development, cathode with the formula Li(M0.5Mn1.5)O4 , which employs copper might appear on the market.

In Table 1, average material composition of traction batteries for different cell types. Here, NMC, NCA, and LFP refers to LiNi0.33Mn0.33Co0.33O2, LiNi0.8Co0.15Al0.05O2, and LiFePO4 batteries, respectively.(12)

Table 1: Avarage material comparison of traction batteries for different cell types. All values in g/kg. Adapted from (11)



Cell type	NMC	NCA	LFP
Battery Cells			
Total	630	598	530
Active cathode material	191	175	173
Lithium	*14*	*13*	*7.6*
Cobalt	*39*	*16*	*0*
Nickel	*39*	*86*	*0*
Manganese	*36*	*0*	*0*
Aluminum	*0*	*2.5*	*0*
Iron	*0*	*0*	*61*
Phosphorus	*0*	*0*	*34*
Oxygen	*63*	*58*	*70*
Cathode foil (aluminum)	39	40	34
Electrolyte	114	101	85
Separator	54	50	43
Active anode material (carbon)	140	131	111
Anode foil (copper)	66	70	60
Cell casing (aluminum)	21	20	17
Others	6	10	8.5
Total	370	402	470
Wiring	21	50	64
Copper	*13*	*30*	*38*

In table 1, copper is also responsible for wiring and other purposes. Total copper amounts in traction batteries account for the range between 100-162 gr per kg of battery depending on different cell types. In percentage terms, copper occupies **15.8 –**

30.5 % of total battery mass. A study (4) also states that copper comprises almost **45%** of the MF of battery manufacturing on average.

However, in the future, possible anode materials with higher capacity which consists of composites like C/Si, Si alloys, and non-Si alloys, might be drastically emerged since Si holds great potential as an anode material because of its bond with 25 times more lithium ions than graphite the main material use in today's LIBs. Additionally, partial replacement of Ni by Co and Al leads to better stability and extended cell life. However, the research aims at further Co reduction due to its high toxicity as well as the relatively high price (30).

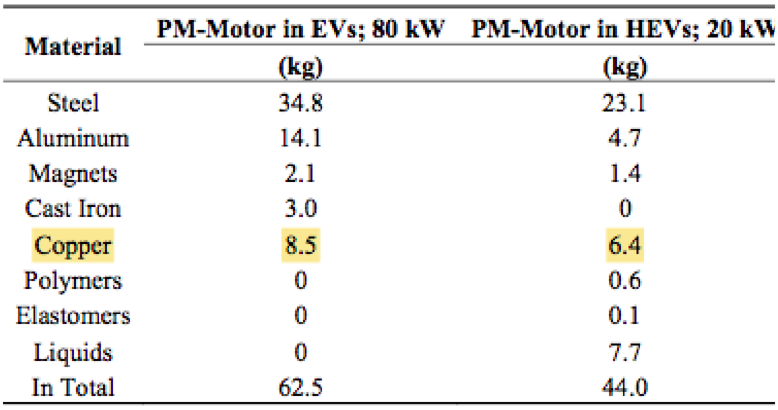
Nevertheless, it is difficult to foresee whether it affects copper use in anode.

3.1.2 Electric Drive Motors

In constrast to traction batteries, copper occupies huge fraction in electric drive motors as it deals with electrical energy. Although various types of electric motor including direct current (DC) motors, synchronous motors, induction motors, and switched reluctance motors are commercially available, as of now, permanent magnet (PM) synchronous and induction motors are utilized in electric vehicles the most commonly. (12) In 2018, Elwert et al. (12) indicated that permanent magnet (PM) is the dominant technology for modern EVs due to the general interest in light-weight construction. You can see typical material composition of permanent magnet synchronous motors in both EVs and HEVs from Table 2.

Generally, cast iron, aluminum, steel, and copper are considered as fundamental elements of modern electric motors. Main function of copper in PM-motor is to converts electric energy to mechanical energy and its copper body consists of refined coil wires. A study (14) sttate that a pure electric vehicle can contain more than a 1600km of copper wiring

Table 2: Typical material composition of permanent magnet synchronous motors. Adapted from (11).



Material	PM-Motor in EVs; 80 kW	PM-Motor in HEVs; 20 kW
	(kg)	(kg)
Steel	34.8	23.1
Aluminum	14.1	4.7
Magnets	2.1	1.4
Cast Iron	3.0	0
Copper	8.5	6.4
Polymers	0	0.6
Elastomers	0	0.1
Liquids	0	7.7
In Total	62.5	44.0

in its stator windings. As EVs with PM motor of 80 kW consumes 8.5 kg copper in its body, battery electric buses with PM motor of 200 kW would consume around 22 kg copper.

However, there is no proof that EV manufacturers continue to consume PM motors in the future like now becuase PM motors face some issues due its NdFeB magnets usage. According to a study(12), consumption of REE in the magnet reach 30% of its total mass, mostly neodymium and dysprosium with minor amounts of terbium and praseodymium. Regarding the difficulties in REE production, many motor manufacturers and scientists target to minimize motor dependency on REE(16).

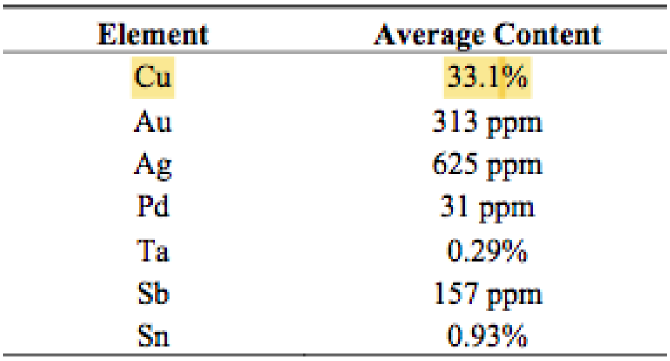
Therefore, it is difficult to estimate copper comsumption in electric drive motors accurately in term of future

3.1.3 Power Electronics

The EVs power electronics is a set of sub-components, namely the inverter, the DC voltage converter, the printed circuit, an onboard-charger with an AC-DC converter(12). Its main function is to optimize the energy flow in the electric vehicle which is generated from the traction battery.

In the following table 3, material content in the printed circuit board which is one of the sub-components of the power electronics is shown.

Table 3: Average valuable metals share in printed circuit boards of selected power electronics module. Adapted from (11).



Element	Average Content
Cu	33.1%
Au	313 ppm
Ag	625 ppm
Pd	31 ppm
Ta	0.29%
Sb	157 ppm
Sn	0.93%

As the main task of copper in power electronics is to conduct electricity, copper accounts for one third of the total content.

However, increasing an energy efficiency of a power electronics is still in need and being lighter and more compact power electronics modules is essential for further development of the EVs.(12)

3.2 Copper recyclability from end of life EVs

As emphasized by Burak et al. (4), the recycling rate of copper at the end of life electric vehicles is around 95%, whereas it is 90% for wrought and cast aluminum.

Technically, future innovative technologies and appropriate policies should continue to contribute to copper recycling innovation. Regarding the drastic development of electric mobility, new components and materials tend to appear in the market rapidly, which causes new challenges regarding its recyclability. Therefore, rapid discoveries of new technologies and development is of utmost importance in term of recycling.

As you can see previous sub-chapters, copper is involved in EVs as anode collector foil in a traction battery, up to 1600 km long coil in a motor, which converts electric energy into mechanical energy and lastly connection wires which optimize electric flow throughout entire EVs body. Copper recyclability directly depends on techniques and methodologies that can deal with the recycling of traction batteries, electric motors, and power electronics.

According to Elwert et al.(12), general EV recycling has the leading 4 steps, namely de-pollution, dismantling, shredding and post-shredding sorting.

First of all, de-pollution process takes place in authorized treatment facilities to get rid of toxic and hazardous materials or parts in feed, such as operating liquids, airbags, and batteries. Secondly, specific components such as catalysts, engines, power electronics, and tires are dismantled, followed by shredding and crushing steps. In this phase, the bodies are is disassembled into smaller particles by mechanic forces and they become to able to classified by size difference. After classification, small particles mix are usually sorted according to physical properties. Overbelt magnetic separator, eddy-current and density separator are usually involved in the process to separete ferrious metal, non-ferrous metal, and light materials, including plastic, respectively.

It shows that copper is obtained from the recycling process in a mixture with other non-ferrous scraps. However, it is worth saying that copper in engine and batteries is not included here and it requires specific treatment to recover.

Although copper has a favorable potention to be treated without any loss of performance, it makes high-grade copper consumers impossible to use them instead of primary source copper in reality as the outlet from EVs recycling process tends to have a high impurity.

4 Copper availability

In this chapter, you can find the answers for the following quistions:

- What percentage of copper demand is due to EVs alone by 2040?
- Is there enough copper reserves and capacities to provide this demand?

4.1 Application fields and Market Outlook

Copper has many desirable attributes that promote its widespread use in many applications across a number of end-use markets. However, its key property is that it is an excellent conductor of electricity, with 70% of total consumption solely due to this characteristic. It is mainly used as the conductor core in wire and cable and in electrical parts and connectors. These generally represent the highest added-value applications for copper.Copper is also an effective conductor of heat, which represents a further 10% of its applications, mainly in tubes and pipes in heat exchanger devices. Copper is also malleable, ductile, machinable, formable, corrosion-resistant, antimicrobial and aesthetic which consumes for the remaining 11% of all other areas of use measured by property. Copper can be alloyed with other metals such as zinc (to form brass) or tin (to create bronze), and many other metals to develop new features for different applications.

In EVs industry, its being electricity and heat conductive characteristics is hired.
Total copper demand in electrical applications is predicted to grow at a compound annual rate of 2.2% and contribute just under 84% of all the tonnage increase over the forecast period. Heat transfer applications should grow at a faster rate of 2.6%py and will provide just under 13% of all of the increase while demand in other properties will rise by just 0.8%py to generate only 3.5% of all projected consumption growth (35).

n general, refined copper is used in those applications where electrical conductivity is paramount, ensuring supreme reliability over a very long product lifetime. An example is wires and cables that use very small conductor sizes, such as electric motor windings or electronic leads or flexes. Refined copper enables wire rod to be drawn efficiently down to very fine diameters with a very low incidence of wire breaks that might otherwise harm equipment productivity. Although It is also one of the most recycled metals as it can be endlessly reused without any loss of performance, cheaper wire rods made from recycled copper contain more impurities that increase the risk of wire breaks at lower diameters, which outweigh any initial cost savings. However, the industry claims a global Recycling Input Rate of 35% that enhances copper's green and sustainability credentials (35).

Over the forecast period, we are projecting that total copper consumption in all forms will increase from 30,6Mt in 2018 to 43,6Mt by 2035 at a compound annual growth rate of 2,1%. Based on projections of world population growth, this implies that the world total consumption per capita will advance from 4,0kg in 2018 to 4,5 kg by 2025 and 5,0kg by 2035. The primary demand drivers are growth in population, gross domestic product, urbanization and the resultant increase in demand for electricity for heat, light and power in utility distribution networks, buildings, equipment and devices.

It should be noted that this data does not take into account the potential rise of the electric vehicle industry in the next decades.

4.2 Copper demand in the EV industry in future

The potential impact on copper demand is not just the rate of growth of EVs, but also the mix of EV types and the type of vehicles such as automobiles, SUVs and commercial vehicles. It is evident that the closer that an EV becomes to replicating the performance of ICE, the more copper content it will require to do so. It might wait mid-2020s before the copper industry sees the incremental tonnage growth over traditional ICEs.. The three positives are: a rising average intensity of copper per vehicle, more copper cables in **charging infrastructure**, and eventually a need to selectively upgrade parts of the **low voltage distribution power grid** that are unable cope with the additional electricity demand. Given the many possible variables in the forecast it is impossible to be too precise on the ultimate positive impact on copper demand. However, by 2035 it is estimated that the incremental gains in EVs alone over their ICE equivalent might range between **1.85-2.25Mt**. On top of this are the gains in the network infrastructure (charging cables and grid upgrades) which we estimate may range between **1.25-1.75Mt**. This is divided **0.5-0.6Mt in charging cables** and **0.75-1.15Mt in distribution grid upgrades**. The center point of these combined estimates is **3.55Mt** of additional copper demand by 2035 which would alone represent an **11-12%** increase on world demand in 2018 (35).

EV users will have a slow charging cable to use at home, usually overnight, but they will also need a broad network of charging stations across the country. This would include work places, kerbside parking, car parks, train stations, airports, shopping centres, supermarkets, petrol stations and motorway service stations, etc. In order to ensure that the charging infrastructure is ready, governments may bring in legislation to ensure that all-build housing and multiple dwelling units must have charging points pre-installed (35).

Based on those data and and EV's copper consumption, a specific study is done to estimate the impact of electric vehicle sales on the copper industry and explained here.

Detailed explanation:

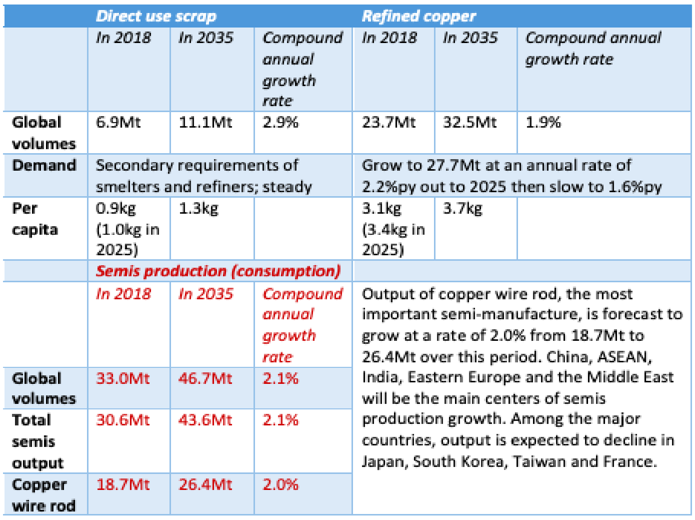
Given data: (obtained from the research report introduced earlier)

1. Total copper consumption in all forms will increase to 43,6Mt by 2035 at a compound annual growth rate of 2,1%. (Table 4.)
2. Passenger EV sales to rise to 10 million in 2025, 28 million in 2030 and 56 million by 2040. (p.13)
3. There is an estimated 20-25kg of copper in internal combustion engines (ICEs), ~40kg in hybrid electric vehicles (HEVs), ~60kg in plug-in hybrid electric vehicles (PHEVs) and ~83kg in battery electric vehicles (BEVs). (p.23)

Assumptions:

1. The data given may vary due to some unknown factors; such as China's total demand of copper is underestimated because China does not provide exact numbers in regards to its resource demands.
2. The calculation shows a case where a BEV takes 100% of all vehicle sales alone.

Table 4: Compound annual growth rates of direct use scrap and refined copper respectively in 2035. Adapted from (35).



	Direct use scrap			*Refined copper*		
	In 2018	*In 2035*	*Compound annual growth rate*	*In 2018*	*In 2035*	*Compound annual growth rate*
Global volumes	6.9Mt	11.1Mt	2.9%	23.7Mt	32.5Mt	1.9%
Demand	Secondary requirements of smelters and refiners; steady			Grow to 27.7Mt at an annual rate of 2.2%py out to 2025 then slow to 1.6%py		
Per capita	0.9kg (1.0kg in 2025)	1.3kg		3.1kg (3.4kg in 2025)	3.7kg	
	Semis production (consumption)					
	In 2018	*In 2035*	*Compound annual growth rate*	Output of copper wire rod, the most important semi-manufacture, is forecast to grow at a rate of 2.0% from 18.7Mt to 26.4Mt over this period. China, ASEAN, India, Eastern Europe and the Middle East will be the main centers of semis production growth. Among the major countries, output is expected to decline in Japan, South Korea, Taiwan and France.		
Global volumes	33.0Mt	46.7Mt	2.1%			
Total semis output	30.6Mt	43.6Mt	2.1%			
Copper wire rod	18.7Mt	26.4Mt	2.0%			

Estimated result of the calculation:

By 2035 it is estimated that the incremental gains in EVs alone over their ICE equivalent might range between 1.85-2.25Mt. (p.30)

Calculation Process:

There is 83kg of copper needed in an average Passenger EV, which is 0.083T.

If the rise in sales of EVs in 2025 is 10 million > 10 million cars x 83 kg = 0.83Mt of copper will be EV gain. (see Table 5.)

Continuing the calculation in the same way, we get the result of years 2030, 2040 and those of other types of EVs in the following table.

Table 5: Result of the calculation

	Amount of copper	Rise in sales of EVs in 2025 = 10 million	Rise in sales of EVs in 2030 = 28 million	Rise in sales of EVs in 2040 = 56 million	Global demand increased by EV sales (2035)
BEV	83kg=0.083T	0.83Mt	2.34Mt	4,648Mt	8%

Considering that we have the data of copper demand in 2035 (43,6Mt), the next step is to estimate the EV sales gain in 2035 from the datas of 2030 and 2040. The average = 3.494Mt of copper gain only in the EV industry. Which means the total demand will become = **43,6Mt + 3,494Mt = 47.094Mt** .The demand increased by **8%.**

In comparison with the another study (5), this result seems to be relatively higher than the result of study that estimated demand for copper due to electric vehicles as 1,700 kilotons by 2027.

4.3 Global copper reserves

According to the Reilly II (2019), the future availability of minerals is subject to the concept of reserves and other identified resources, undiscovered resources which will be discovered in the future, and material that will be recycled from currently being used stocks of minerals or from minerals in waste disposal sites. While reserves refer to deposits that have been discovered and assessed to be economically profitable, resources refer to a far greater concept that includes both identified and undiscovered deposits that are prognosticated based on a preliminary geological survey. As of 2019, total world copper reserves are assessed at 830 million tonnes and yearly demand is rated at 28 million tonnes. (16) (see Figure 6.)

In 2013 the U.S. Geological Survey (USGS) completed the first-ever a geology-based, cooperative international estimation of global copper resources for the two most significant deposit types, namely that porphyry copper deposits which are dispersed in igneous intrusions and sediment−hosted strata bound copper deposits which are concentrated in sedimentary rock. The individual undiscovered totals for porphyry and sediment−hosted deposits are 3,100 and 400 Mt respectively, bringing about a global total of 3,500 Mt of copper. As a result, total global copper resources (undiscovered + identified) are assessed at 5,600 Mt, including identified copper resources that are estimated at 2,100 Mt so far. (2) As a result of the U.S. Geological Survey (17), the research team found that South America is the predominant source for both identified and undiscovered porphyry copper resources. Furthermore, several regions of Asia including China have also a remarkable potential for undiscovered porphyry copper assets.

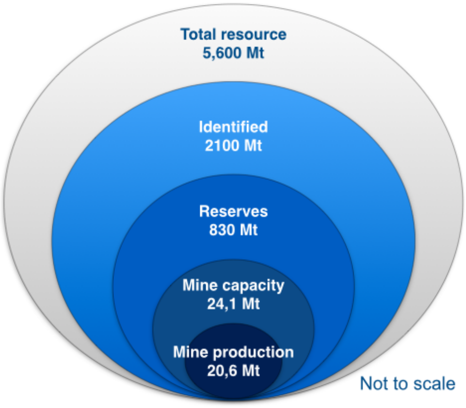


Figure 6: 2018 World Copper Resources, Reserves and Mine production. Adapted from (2)

In case of sediment-hosted stratabound copper deposits, sedimentary basins in the Northwest Botswana Rift in Botswana and Namibia, the Benguela and Cuanza Basins of Angola, and the Cambrian rocks of Egypt, Israel, and Jordan are evaluated as having huge potential for undiscovered copper resources; however, these regions require extra examination, research, and assessment (17). In addition, North America has huge influence for an identified copper resource among states, Arizona was considered as the leading copper-producing State and was responsible for about 66% of domestic output, followed by Utah, New Mexico, Nevada, Montana, Michigan, and Missouri (16)

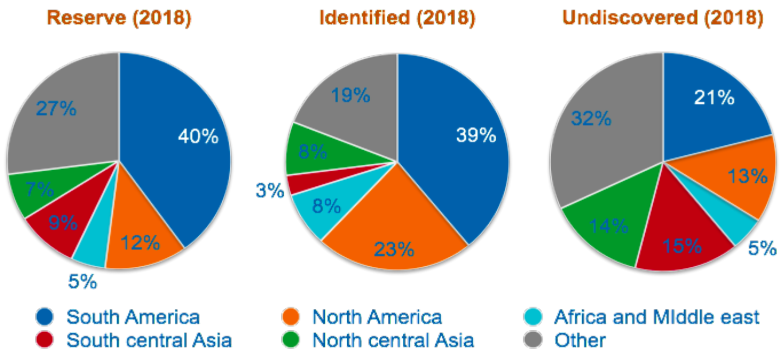


Figure 7: Global distribution of identified and undiscovered copper resources. Adapted from (2)

4.4 Long-term availibility of copper

According to the International Copper Study Group (2) experts assume that it is exceptionally impossible to run out of copper. They come up with this assessment because of the following three main reasons.

At first, United States Geological Survey annual studies have been confirming that increases in reserves have grown despite increased demand for copper. In the period 2008−2018, 197 million tonnes of copper have been mined. In that same period, however, reserves have grown by 280 million tonnes. This reflects additional exploration, technological advances and the evolving economics of mining. (18)

In the second place, technology plays a key role in addressing many of the challenges faced by new copper production. Experts assume that known and as yet unknown innovations will ensure new mine production continues to provide vital copper supplies.

In addition, copper recycling has to be considered as an essential part of copper availability since today’s primary copper is tomorrow’s recycled material. (2). The most significant advantage of copper recycling is that copper can be recycled repeatedly without any loss of performance.

On the other hand, experts believe that copper will continue to be an inseparable and affirmative contributor to industry innovation and sustainable developments in the future based on the latest knowledge and data on geological availability.

5 Environmental footprint for copper production

5.1 Primary source copper production

As Nilsson et al. state (13), the base-metal producing sector is under increasing public pressure due to energy and water footprints and number of challenges need to be overcome including increased demand and larger resource use in respect to lower ore grades. Entire processes to produce high-grade Cu include the stages of extracting, concentrating, smelting, and refining.

Mining: The extraction of copper-bearing ores is the first step of primary copper production. There are three basic types of copper mining, namely surface, underground mining, and leaching. Among them, open-pit mining is the predominant mining ways all around the world (19)Since 1900, world production was less than 0,5Mt copper whereas world copper mine production reached 4Mt by 1960s, as of 2018 it has grown into a total of 21,6Mt copper (20). Concentrate and SX-EW are considered as two main processes of extracted copper. While there was no virtual existent of SX-EW technology before the 1960s, this stood now at 3.9 million tonnes in 2018. The studies state that this gain will continue to increase in the future.(21) The most influential region in copper mine production is Latin America and the countries, including Chile and Peru which provide 42% of world total copper mine production as of 2018. As of 2018, the world copper mine capacity is recorded as 24,1Mt and it is expected to reach 28,9Mt in 2023 (2)

Concentrator: After the extraction step, copper is crushed and ground followed by a concentration by flotation. In this process, copper concentrating on the product typically reaches around 30% of copper, but grades can range from 20 to 40 percent(2)

Smelter: In the following smelting process, sometimes preceded by a roasting step, concentrated copper is transformed into a "matte" containing 50-70% copper. Smelting is the pyrometallurgical process used to process copper products, which have up to 98.5-99.5% copper content. This end product of the smelting process is called blister copper (19). As of 2018, world copper smelter production reached 20.1 million tonnes of copper and Asia, in particular, China has a huge influence on production. Apart from the primary smelter, secondary smelter which use copper scraps as their main source of feed is also plays an important role. Within the last 40 years, secondary feed smelter production reached more than 3Mt that was 0,3Mt in 1980 (13). As of now, the following 5 main technologies are applied all around the world: Flash/Continuous, Modified Reverb/Convert, Chinese technology, Reverb/Black/Rotary, and Electric. Among them, the use of Flash and Continuous technology accounted for 69 % of total copper smelter capacity in 2018. (2)

Refinery - In the final step, the blister copper goes to the refinery and re–melted and cast into anodes for electro–refining. The output of electro–refining is refined copper cathodes, assaying which is over 99.99% of copper. Since the 1980s, secondary refinery technology was introduced, and as of 2018, almost 5Mt out of 27,2Mt of world refined copper is produced with refinery from the secondary feed. (2) The leading technologies in copper refinery industries are Electrolytic, Electrowinning, and Fire Refining. While the world copper refinery capacity is 27,5 Mt in 2018, it tends to reach 32Mt by 2023. The most influential region by refined copper production is Asia which accounted for 13,5Mt alone in 2018. (2) There are variety of LCA publications on Cu production from primary sources are available, however only a few describe the production of Cu metal from the secondary source.

As retrieved from the Ecoinvent 3.3 database, Average Carbon footprint (CF) ranged from **2.1 to 8.0 CO2-eq/kg Cu.** In the study (13), available data on the CF was compared and analyzed due to the copper production. Its According to this comparison, average Cf was in range between **1.1 to 8.5 CO2-eq/kg Cu.**

In general, those CF values can vary depending on the use of different ore grades, mining methods, and fuel sources for the smelting heating and electricity generation. (22) According to the comparison made by Nilsson(13), a similar observation was made by a number of studies which aims to determine the overall energy consumption by technology used or to show the variation from one mining to another mining or just to analyze geographically dependence. One of the studies analyzed by Nilsson (13) states that 30%–70% of Cu production variability can occur from different mining sites. It is shown that only the mining and processing processes can occupy 30%–70% of the the total CF in copper production. mining sites. Additionally, It is shown that only the mining and processing processes can occupies 30%–70% of the the total CF in copper production.

5.2 Second source copper production

The European non-ferrous metal recycling industry is rated as the most advanced in the world when compared to other developed countries such as the US, Canada, and Japan(23) . This is directly related to the fact that the EU's non-ferrous metal sector relies mainly on imported raw materials. Therefore, the escalating the use of secondary raw materials and implementation of innovative and energy-efficient technologies for the production of the respective metals receive much attention from the decision-makers in the EU The average demand of the secondary source copper production in the EU reached 40% in 2011. In contrast, the global demand was close to 35%. (13).

According to the Copper Development Asssociaton inc (33), more than 30 % of world annual copper use are estimated to be secondary source copper for the last ten years. From an economic point of view, recycled copper is valued at 6451 US$/t, grade A, LME. (12) However, in 2018, this demand is significantly reduced because the Chinese tightened scrap import controls by switching eight types of waste and scrap – including copper and aluminum – from its "non-restricted" to its "restricted" list for importation. (24)

From a technical capacity perspective, more research and development in all stages of the secondary copper life cycle is needed to find truly sustainable solutions. The development of metal production technologies from secondary sources should be supported and motivated well through policies within a framework of increased sustainability(12).

Copper is one of the few metals that can be recovered from the majority of its end-products and returned to the production process without any performance loss during recycling. (25) In the context of secondary source Cu production, two main terms should be discussed, the namely direct melt of “new scrap” and the recycling of “old scrap” New scrap refers to the waste resulting from either metal discarded in semis fabrication or generated during the initial manufacturing process while old scrap is often contaminated to a certain degree, depending mainly on its origin and the efficiency of its collection systems.

In terms of Carbon footprint, CF of secondary source copper production is was in range between **0.2 and 1.9 kg CO -eq/kg Cu.** As concluded by Nilsson et al. (13), the variation depends on the quality of the source material, the metallurgical process used and the exclusively transportation process.

With few exceptions, the production of metals from secondary sources has generally been reported to have lower CFs than the production from primary sources. (12, p.9)

The main differences are defined that to have more dependency on the first steps of the processes. In the case of primary Cu production processs, mining and concentration processes make a lot differences, while disassembly, sorting (according to different levels of purity), and transportation steps should receive attention in case of the secondary Cu production process.

6 DISCUSSION

The following table shows the calculations which indicate the amount of environmental footprint(CF as the indicator) caused by the copper production process, which is only for the EV industry in the next 20 years. In order to estimate the benefit from the secondary source copper production, the additional comparison is made.

Detailed explanation:

Given data: (obtained from the research report introduced in the previous chapter)

1. Copper demand for EV industry alone: **3,494Mt**
2. CF for Primary source copper production: **1.1 to 8.5 CO2-eq/kg Cu.**
3. CF for Secondary source copper production: **0.2 and 1.9 kg CO-eq/kg Cu.**

Assumptions:

1. The calculation shows a case where copper production required for the EV industry uses 100% of either primary source copper or secondary source production.

Calculation Process:

Since the given value for CF is between some range, both the minimum and maximum value is calculated by multiplying total copper demand for EVs (3.494 Mt) and respective value of kg Co-eq per kg of copper.

Table 6: Result of the calculation

Copper production source	kg CO-eq/kg Cu	Copper demand for EV by 2035	Total releasing tn CO -eq in ton
Primary	1.1 to 8.5	3,494Mt	**3,843 Mt – 29,69 Mt**
Secondary	0.2 to 1.9	3,494Mt	**0,699 Mt – 6,638 Mt**
Difference			**3.114 Mt- 23,052 Mt**

Based on this result, we can see how the use of secondary source copper production can mitigate the amount of CO-eq that could have released by primary source coper production. In percentage terms, it would be translated that **78 %** of environmental benefit can be resulted on average. However, It is an absolute number, and in reality, there is almost no gap in EV industry to use pure secondary source copper in their product. As I stated earlier, the uncertainty of secondary source copper products makes high-grade copper consumers impossible to use them instead of primary source copper and EVs industry is undoubtedly one of the upgrade copper consumers. However, the innovative technology for purifying the recycled copper can be expected to develop up to the required level.

On the other hand, we need to take the environmental footprints into account due to the copper recycling from the EV industry. As mentioned earlier, the recycling of the LIB is receiving a lot of attention from scientists and experts in recent years.

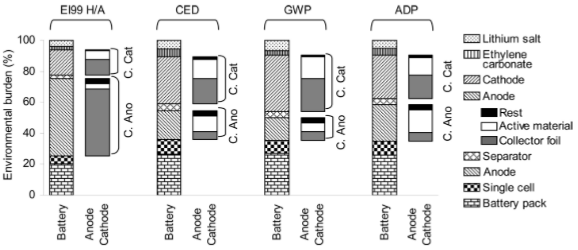


Figure 8: Environmental burden of the main components of the Li-ion battery and the electrodes expressed with Ecoindicator 99 H/ A (EI99 H/A), cumulated energy demand (CED), global warming potential (GWP), and abiotic depletion potential (ADP). Components of the anode (C. Ano), components of the cathode (C. Cat). Adapted from (3)

If we focus on copper alone, it is employed in a batteries anode as collector foil. According to Notter et al. (3), the cathode collector, made of aluminum foil, has a higher share of the environmental burden than any active material throughout all impact assessment methods. Therefore, anode copper collected foil is grouped as parts that cause a minimal environmental burden. (see Figure. 8)

A study (26)that surveyed EVs battery recycling pathways stated that some environmental-friendly battery recycling technologies could have appeared soon and it can reach to potential net savings of 1–2.5 kg CO2/ kg of battery recycled which means a battery life-cycle emissions can be reduced by up to 7%–17%. However, it is necessary to keep in mind that it can vary affected by the energy usage of recycling processes and location of recycling.

The important thing is that only CO2-eq cannot be the competitive representor of the environmental impact and it is necessary to conduct LCA on this to indicate the environmental benefit of secondary source copper consumption more accurately. The main difference between CF and LCA is that CF only considers the emissions of CO2-equivalents (CO2-eq), while LCA covers a broader spectrum of impact categories(3).

From another angle of view, we have to look at whether there is a sufficient amount of copper resource and copper supply to provide this rapid increase in copper demand that we calculated. If we compare this calculation with the date of copper in the first section of the report, while copper demand in 2035 is 47.094Mt, the total resource of copper is 5600Mt and the total reserve is the total reserve 830Mt. It is obvious that there are no temporary shortages that will be occurred because of the lack of resources in the near 100 years if the annual demand is assumed 50 Mt. However, problems may arise in the supply chain aspects of copper production. For example:

According to Reilly et al. (16), 2019, world copper mine production and the mine capacity of copper are 20,6 Mt and 24,1 Mt respectively. In 2018, world copper smelter production reached 20,1 Mt. Furthermore, world copper refinery production accounted as 24 Mt, while its capacity is around 27,5Mt.

Here, we can see that we have not yet enough capacity and facilities to produce the calculated copper amount for 2035. As of now, the total world supply chain capacity is available for only around 28Mt copper production. (16)

On the other hand, the ratio between production rate and capacity rate in each copper production sector looks affirmative. Being constantly lower than the capacity rate in all of the minings, smelters, and refineries indicate that it is not yet working at full capacity and they have always developed situations in each sector including new technologies, facilities and also manpower.

In addition, the influence of copper recycling in the world copper market is continuously increasing year by year. During the last decade, more than 30 percent of annual copper use came from recycled sources. (12)

For these reasons, we can assume that the capacities in all production steps of copper would increase concurrently with growing demand and there will be no problems concerning copper production shortage in the future because of the high probability and availability in each sector of copper production to ensure the amount of copper that can meet the demands by contributing innovative technologies and developing the facilities.

Policies and decision-makers have still a major role on electric mobility growth. EV uptake usually starts with setting a set of goals, followed by vehicle implementation and charging conditions. There exist Fiscal incentives, especially as long as the selling price of EVs is higher than that of ICE cars, which are often paired with legislative initiatives to improve the market proposition of EVs (e.g. exceptions of requirements, reduced tolls or parking fees) or to implement zero-emission regulations.

Plus, technology developments continue to have a significant influence on EVs recyclability and cost reductions.

7 Conclusion

In this report, we aimed to find thorough information about copper’s role in the electric vehicle industry. Continuing, the main focus was mainly pointed at the ecological aspects of copper in the EV industry. Especially copper's potential resource availability was searched when the electric vehicle sales will rise exponentially.
Within this frame of work, I calculated an estimation of carbon footprint (CF), which can be generated by primary and secondary source copper production for the EV industry as of 2035. This calculation is based on the estimation of 2035 copper demand with consideration of EV's increase in sales, which is also made by Zayabolor and I.
As a result, it is shown that CF that could have generated from primary source copper production can be reduced by up to **78%** if the EV industry consumes 100% secondary source copper production in their product. However, to have more precise results, it is needed to evaluate the optimized ratio of primary to secondary source copper products.

Moreover, in order to make further research on this topic more comprehensive, it is necessary to conduct LCA to covers a broader spectrum of impact categories and to achieve more accurate value because CF only considers the emissions of CO2-eq.

Furthermore, we concluded that a sufficient amount of copper resource is available and the capacities of the copper production would elevate as the copper demand rise. There is a probability that neither temporary nor permanent shortage of copper will occur in the future, even though the drastic increase in electric vehicles.

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