CARBON FOOTPRINT OF AN ELECTRIC CAR IN COMPARISON TO A FOSSIL FUEL CAR

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Electrical Engineering, Bachelor's thesis

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Examiner: D.Sc (Tech.) Dmitry Egorov

ABSTRACT

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Carbon footprint of an electric car in comparison to fossil fuel car

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Electric cars have become very popular in recent years. Especially as the technology has developed to the point where the mile range of electric cars is already good enough for consumers. Electric car prices have also fallen dramatically as the cost of battery production has fallen. For more and more car buyers, electric cars are becoming the most attractive option. Transport is becoming more electric-propulsion-technology-based and traditional combustion engine cars are giving way to electric cars.

This work aims to compare the overall carbon footprint of an electric car and an internal combustion engine car. This contributes to the study of the current state and the future trends in electrified vehicle technology.

As the result of the study done, the following conclusion arise: an electric-propulsion-technology-based car has lower life cycle carbon footprint compared to an internal combustion engine car. In the production phase, the electric car generates ca. 57-59% more carbon dioxide, but these emissions are still reasonable, as an electric car produces less emissions during its use period. After ca. 13000-60000 kilometres the reasonable high production-stage-related-emissions of an electric car are mitigated due to its lower emissions during the use period compared to a regular fossil-fuel-technology-based car. Electrification of transport is an opportunity to reduce carbon emissions, which is seen as a contribution to mitigate a climate change.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

School of Energy Systems

Sähkötekniikka

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Sähköauton ja polttomoottoriauton hiilijalanjäljen vertailu

Sähkötekniikan kandidaatintyö

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Tarkastaja: D.Sc (Tech.) Dmitry Egorov

Avainsanat: Sähköauto, hiilijalanjälki, akku

Sähköautot ovat yleistyneet viimevuosien aikana todella paljon. Etenkin kun teknologia on kehittynyt sille tasolle, että nykyisten sähköautojen ajokantama on jo tarpeeksi hyvällä tasolla kuluttajien näkökulmasta. Sähköautojen hinnat ovat myös laskeneet akkujen tuotannon hinnan laskiessa. Yhä useammalle uuden auton ostajalle sähköauto alkaa olla houkutteleva vaihtoehto. Liikenne on sähköistymässä ja perinteiset polttomoottorilliset autot näyttäisivät olevan väistymässä sähköautojen tieltä.

Tämän työn tavoitteena on verrata sähköauton ja polttomoottoriauton kokonaishiilijalanjälkeä. Tämä edistää sähköautojen teknologian nykytilan ja tulevaisuuden tutkimusta.

Työssä havaittiin, että sähköauto omaa pienemmän hiilijalanjäljen koko elinkaaren aikana, verrattuna polttomoottoriautoon. Tuotantovaiheessa sähköautosta aiheutuu 57-59% korkeammat hiilidioksidipäästöt, mutta tämä ero on kohtuullinen, sillä sähköautossa käytönaikaiset päästöt ovat pienemmät. Sähköauton tuotantovaiheen päästöt kompensoituvat 13000-60000 kilometrin ajon jälkeen pienempien käytön aikaisten päästöjen ansiosta verrattuna polttomoottoriautoon. Liikenteen sähköistyminen on mahdollisuus vähentää hiilidioksidipäästöjä, joka osaltaan lieventää ilmastonmuutoksen vaikutuksia.

ABBREVIATIONS

EV	Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
NMC	Nickel Manganese Cobalt

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1 Introduction

Many countries in Europe have plans to ban internal combustion engine cars completely within the next decade. Italy, for example, is set to ban them completely by 2035 [1]. This decision aims to curb global warming and meet the Paris climate agreement's target of limiting global warming to 1.5 degrees Celsius. [2]. Moving car transport to the direction of sustainable technology is among important targets for the future carbon-neutral society.

In 2017, the transport sector accounted for 24% of all global greenhouse gas emissions, with 74% of this amount coming from road transport [3]. As the climate change threatens nature, these emissions need to be reduced to slow down climate change. If car transportation can be made more environmentally friendly, it will have a considerable impact on a global scale.

Electric cars are thought to be an ecological solution compared to an internal combustion engine vehicle (ICEV). This is mainly because Electric vehicles (EV) does not emit tail pipe emissions at all.

Now that electric cars are more popular than ever, it is worth asking whether they are as environmentally friendly as they are thought to be and is this the right direction when considering climate change. Stopping climate change is vital for people and biodiversity, and therefore it is important to make the right choices towards a greener future.

The development of battery technology has led to 97% decrease in the price of batteries in last three decades [4]. As a result, the prices of electric cars have fallen to the level of internal combustion engine cars and new car buyers are choosing an electric car over an internal combustion engine (ICE) car more often. In addition, lower running costs compared to ICEV are attracting new buyers towards EVs.

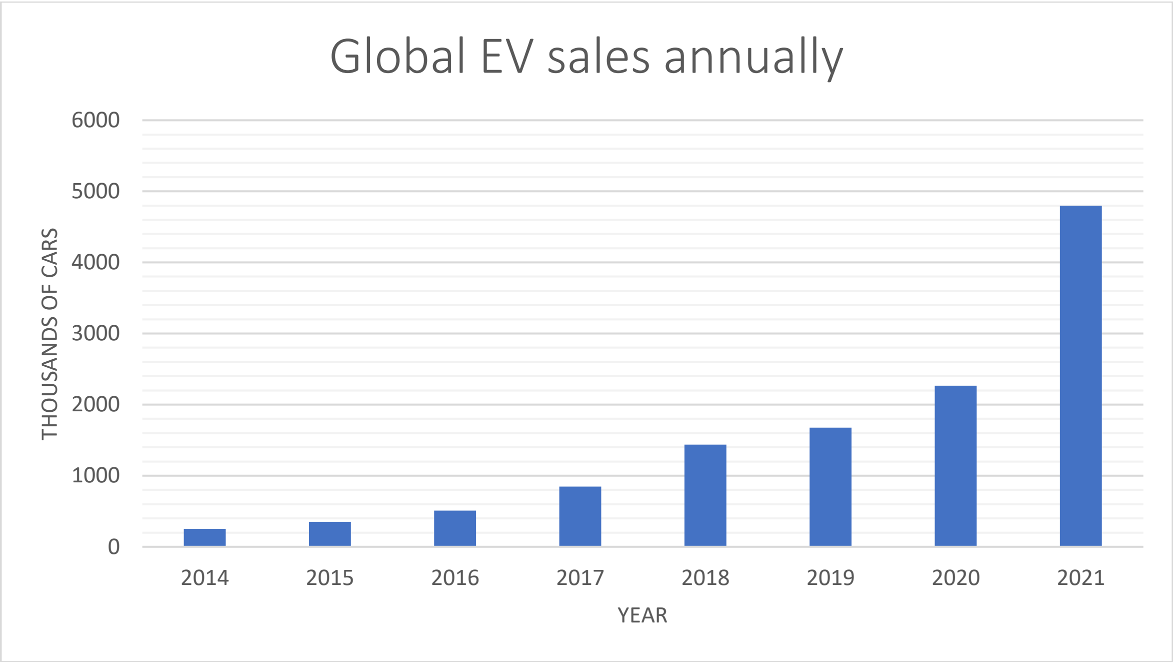

Figure 1: Annual EV sales by year. EV sales are growing rapidly. In 2021, the total number is ca. doubled compared to 2020. In the future, EVs are expected to take even more market share from ICEVs [5], [6].

From Figure 1 it can be seen that EV sales have demonstrated exponential growth during the recent years. It seems that there is huge demand for EVs, and in coming years this trend will likely continue, and we will see huge surge in EV sales.

The objective of this research is to find out if electric vehicle technology is a better solution than internal combustion engine cars in terms of carbon emissions. This work has been motivated by the importance of reducing carbon emissions of cars that is also relevant topic right now.

1.1 Methods

This bachelor’s thesis is based on a comprehensive literature review. There are a lot of research material available on the chosen topic as the environmental friendliness of EVs has been much discussed much during recent years. In this work I will compare new generation ICEVs to new EVs, so already existing car fleet will be ignored.

1.2 Structure

This work contains six sections. First section is introduction which contains background information on this topic and methods used in this study. Second section gives basic information of electric vehicles, e.g. what are the main battery types used and so on. In third section the carbon footprint of EVs and ICE cars will be compared during production and using phase. The fourth part discusses the recycling process of EVs and how used batteries and electronics can be reused after lifecycle of EV. Fifth part discusses results of this thesis and last section is conclusion.

2 Electric vehicle

This section introduces reader to the electric vehicle technology and gives a better understanding of differences compared to ICEVs. The electric-vehicle-technology-related features to be discussed in this section are battery, electric motor types and running costs. There are ICEV and EV structure differences compared in Figure 2.

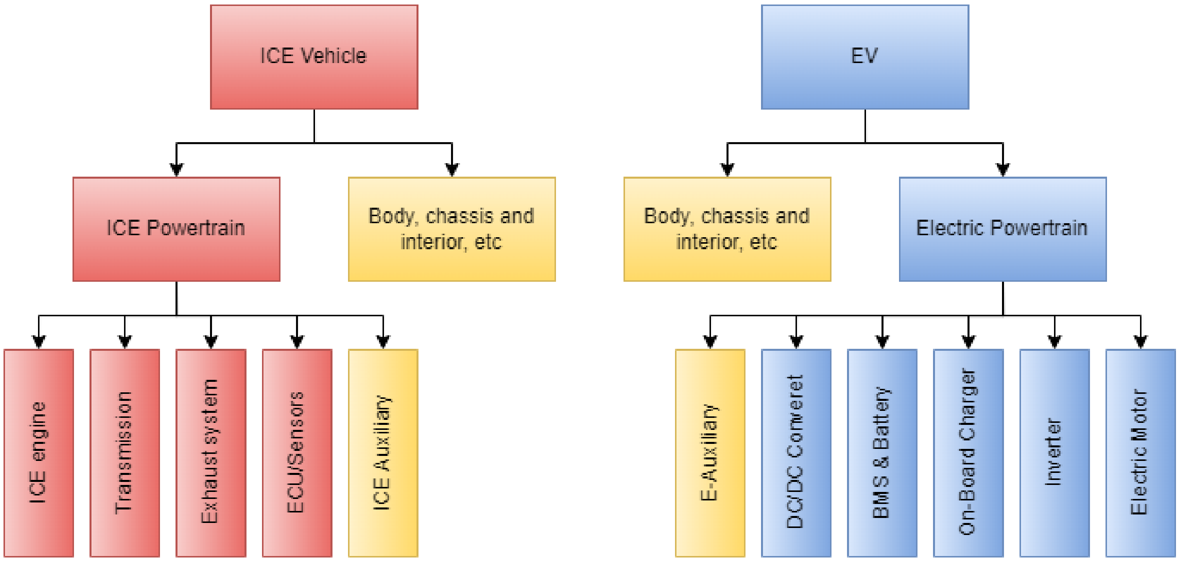

Figure 2: Schematic of EV and ICEV differences. Blue boxes are EV specific parts and red boxes ICEV specific parts. Yellow boxes represent those parts of EV and ICEV that are the same in both car types [7].

2.1 Battery

In this section most common battery types for EVs will be discussed and compared. Also, material availability and battery lifetime will be discussed.

Battery technology is developing rapidly, and new generations of batteries become available in the market relatively fast; the cost of batteries have decreased a lot. Lithium-ion battery pack price were over 1200$/kWh in 2010. After 10 years, i.e, in 2020 the price is 132$/kWh, or 89% drop in price [8]. The present state battery technology still requires considerable improvement in terms of safety, charging speed and energy density. More battery manufacturers have scaled production and invested more in research and development due to high demand for batteries. Battery is the power source of EVs, and most EVs are equipped with lithium-ion batteries. Nickel-Metal hydride batteries are used too but mostly in hybrid vehicles [9].

Lithium-ion batteries have been used many years in electronic devices and it is the best option for EV in today’s technology because they have good efficiency and power to weight ratio, so they have more energy/kg than other batteries. It is very important for electric car because high mass reduces the driving range. Li-ion batteries also can hold a full charge level over time [9].

Lithium-ion batteries with nickel manganese cobalt (NMC) chemistry are most common on EVs today [10]. NMC batteries use lithium, manganese, and cobalt as a cathode material. In addition to NMC-batteries, some manufactures, has started to use Lithium-Iron-Phosphate batteries (LFP). These batteries use lithium-phosphate as a cathode material. The advantages of this battery are that it does not need nickel or cobalt. Cobalt and nickel are expensive metals, so LFP batteries are around 20-30% cheaper on €/kWh [11]. The disadvantages of LFP batteries are lower energy, 90-160Wh/kg whereas NMC cells have 150-220Wh/kg [12]. In other words, LFP batteries have a lower operating range than a battery of the same weight made with different cells. In addition, it seems that cold air has a bigger negative impact on the performance of LFP batteries [13]. LFP batteries on the other hand have better chemical and high temperature stability. Both NMC and LFP are safe batteries, but LFP is the safer chemistry.

2.1.1 Material availability

As electric vehicles become more common and eventually replace all the world’s internal combustion engine cars, the adequacy of materials to produce them will need to be examined. Earth’s resources are limited, and the mass production of electric vehicles requires a large amount of battery capacity. The mass production of batteries is already partly constrained by supply-chain-related problems, as a demand for EVs has grown so much that manufacturers are unable to meet the demand. Scaling up production in relatively slow process. To avoid future problems with battery production, careful consideration and planning is needed to determine which materials should be used in batteries in term of battery performance and sustainability

There are different variations of the NMC batteries currently in use, with different material ratios. NMC-111, NMC-811 ja NMC-622 are one of the most common variations, except NMC-811 is still relatively new on the market. The number sequence indicates the ratio of materials in the battery. The NMC-811 contains a lot of nickel, more than 622 and 111 versions, which makes it energy dense, so it gives a good driving range for EV [10].

Table 1: Required elements for battery. Units of kg/kWh [10].

	Li	Co	Ni	Mn	C
LCO	0,113	0,959	0	0	~1,2
NCA	0,112	0,143	0,759	0	~1,2
NMC-111	0,139	0,394	0,392	0,367	~1,2
NMC-622	0,126	0,214	0,641	0,200	~1,2
NMC-811	0,111	0,094	0,750	0,088	~1,2

Table 1 shows the amount of material required for production for a few different battery models. This allows an assessment of the sufficiency of materials according to future battery demand. There are various estimates of the future battery demand that can be used to draw conclusions about the sufficiency of materials for battery production. According to the study [14], the cumulative need for batteries is estimated for one billion electric vehicles by 2050. This means total capacity of 75TWh of batteries, calculated with an average battery capacity of 75kWh on one car. This battery gives around 300-500 km of driving range, depending on a specific vehicle model [10].

Table 2: Materials for demand. Reserves means total resources on earth [15].

NMC-811	Reserves, m^3	2050 Need, m^3	Need/Reserves
Lithium	$2.10 * 10^7$	$8.33 * 10^8$	0.40
Cobalt	$7.10 * 10^6$	$7.05 * 10^6$	0.99
Nickel	$9.40 * 10^7$	$5.63 * 10^7$	0.60
Manganese	$1.30 * 10^9$	$6.60 * 10^6$	0.01
Graphite	$3.20 * 10^8$	$9.00 * 10^7$	0.28

Table 2 shows reserves and needs of materials. The reserves column shows the total reserves of materials on earth and the demand column shows the total demand for materials calculated according to the estimated demand of 75TWh. The last column shows the calculated ratio of needs and reserves, and if this number is above 1, it would mean that the needs are higher than the existing reserves. According to this calculation, there is no bottleneck in the availability of any of the listed materials. However, cobalt seems to be quite close to the limit of sufficiency in the case of the NMC-811 battery. This could pose a problem, as some reserves may be in a very difficult place to exploit. This calculation does not take mining capacity into account but only material availability. It seems that lithium mining capacity could be a problem in the future [16].

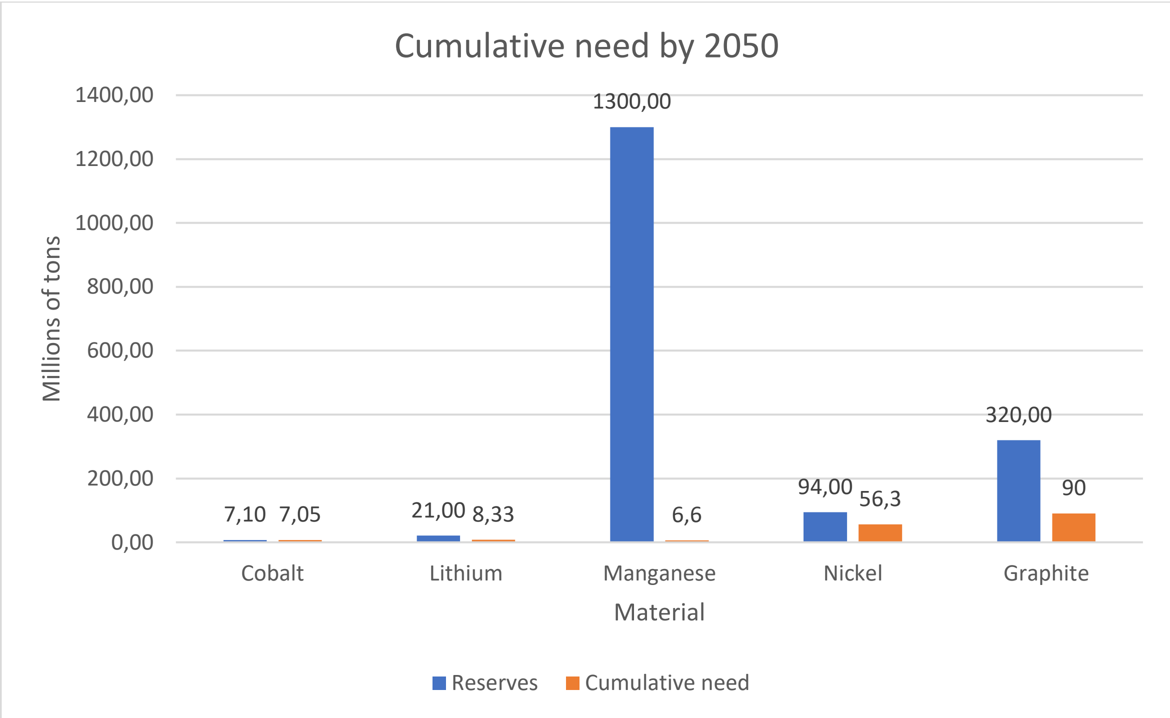

Figure 3. Cumulative material need (in millions of tons) by 2050 for NMC-811 batteries. The presented data shows that reserves of the materials are big enough for estimated needs.

There are Earth's reserves and cumulative material need plotted in Figure 3. In this figure we can see that there should be enough reserves to meet the demand. To be real, this is only an estimate. It can be that real demand for materials is a lot higher in the future. Also, some of the reserves are distributed difficulty on earth, so the utilization of the reserves could be hard and very expensive. Battery technology is improving fast and some alternative battery technologies will most likely solve the possible material availability problem. Recycled materials will be other source for new batteries, when current EVs comes to an end-of-life point and there will be a lot of recyclable batteries to be used for new batteries.

2.1.2 Battery lifetime

Electric car batteries are expensive to manufacture and very expensive to replace, should the need arise, for example, through breakdown. From a financial point of view, but also from an emissions point of view, it is important that electric car batteries are durable throughout the life of the car. It would be very carbon-intensive if there is need to replace electric car's batteries several times over the lifetime of the car. Fortunately, batteries are designed to last at least full life of the car and it is rare that EV battery needs to be replaced with a new one. Currently, Tesla, for example, claims that the batteries they use in their cars can last up to 21-35 years or around 500 000-800 000 km [17]. However, batteries lose peak capacity over the kilometers driven. Tesla, based on data from more than 1 million electric cars sold, has produced a graph showing that after 320 000 km, the battery has about 85-90% of its capacity left.

However, battery life and capacity loss can also be greatly influenced by customer's charging habits, operating temperatures, and the use of the fast charging, among other things [3]. To maximize battery life, it is advisable to keep the battery charge of an electric vehicle at 25-75%, especially for longer storage periods. Storing on an empty or full battery is not recommended, as this will shorten battery life. This applies mainly to NMC batteries. LFP batteries can and should be fully charged to 100% from time to time [18]. Exposure to extremely high temperatures reduces battery lifetime, so avoiding it will keep battery healthier. Using fast charging strains EV batteries and wanes them faster because it presses huge amounts of current in short time in battery, so in favor of extending battery lifetime normal charging speed is better option [19].

2.2 Electric motor

There are many different types of electric motors used in the electric vehicle technology. Some common types of them used in electric cars are induction motor and permanent magnet motor. These motors contain a lot of valuable metals. Induction motors have a lot of copper inside them, and permanent magnet motors may have neodymium used in magnets. Electric motors have very good efficiency, usually more than 95% at nominal operating point. It is much higher than combustion engine which usually have around 30-40% efficiency [20], [21].

2.3 Operating costs

EV's have cheaper maintenance and repair costs compared to ICEV since EVs have much fewer moving parts and there are not many parts that have to replaced and no engine oils to change [7]. Often EVs don't need even brake service as often as ICEVs, because EVs use regenerative braking by motor. It means that electric vehicles can covert the kinetic energy of the car to electrical energy with the motors during deceleration or in downhill. Generated electrical energy can be stored for example back to battery or to ultracapacitor. Regenerative braking can improve the driving range up to 10% [22]. Because of regenerative braking normal day to day driving EVs often do not need to use normal disc brakes. In addition to lower maintenance, the "fuel" for EV is a lot cheaper than gas or diesel. Even though electricity price has risen lately, it is still much cheaper than regular types of fossil fuel.

Table 3: Fuel prices in Europe [23], [24].

Fuel	**Price**
Gasoline	1.75 €/l
Diesel	1.683 €/l
Electricity	0.2322 €/kWh

Table 3 depicts prices for different fuel types. With these numbers the cost of driving can be calculated. Real world consumption of gasoline cars assumed to be 7.2l/100 km [25]. Fuel costs of gasoline car is 12.6€ and 12.12 for diesel car to drive 100 km. For electric car, same amount of driving costs only 4.53€ on 195Wh/km energy consumption. Compared to gasoline car, EV has around 65% smaller fuel expenses.

3 Carbon emissions

In this section the carbon footprint of electric cars and ICE cars will be compared. The carbon footprint of electric cars is influenced by many factors. The manufacturing process is influenced by the country of production and especially by where the materials are sourced. The best possible option is to use local resources as much as possible. If materials are shipped from the other side of the world, more carbon dioxide is emitted per car.

According to the study [26], no technology comes out on top when comparing emissions of cars with different powertrains. Emissions just occurs in different phases of vehicle technologies lifetime, for example EVs driving emissions are low compared to ICE cars but production is more carbon intensive for EVs. So, emissions during different phases just even out between these technologies and they are around same level with each other.

Tesla on the other hand claims almost the exact opposite. In their climate impact report [27] Tesla says that their electric vehicles emit only a little bit more carbon emissions. There are a lot of other studies that supports Tesla’s claims. Most of studies made comparing EV and ICEV carbon footprint are in favor of EV, but different result of studies may be because of different study methods and some of them are more broadly made than others.

3.1 Carbon footprint comparison

The carbon footprint of an electric car's entire life cycle consists of carbon dioxide emissions from its production phase, in-use emissions, and emissions from recycling phase. Of course, the same applies to internal combustion engine cars. Compared to production emissions, an electric car has a larger carbon footprint than a comparable internal combustion engine car. The main reason for this is the battery manufacturing process and the emissions it generates [28]. The carbon footprint of production is also affected by the type of electricity used in production, and this applies to both electric cars and internal combustion engine cars. However, an electric vehicle does not directly emit emissions during the use phase, but the emissions during use are also estimated through the method of electricity production that charges the battery. It can therefore be concluded that the life cycle emissions of an electric vehicle depend mainly on where it is used and charged. If it is charged with electricity from renewable energy sources, then the in-use CO_2 emissions are truly zero.

One difference between the carbon footprint of electric cars and internal combustion engines is that emissions during the use of car will decrease as electricity production moves to more clean forms. For example, electricity produced in Norway is almost completely renewable, so charging electric cars there is much cleaner than in China, where a lot of coal power plants are used to generate electricity [29], [30]. The emissions of an internal combustion engine car, on the other hand, remain the same throughout its lifetime.

3.1.1 Production

The emissions from the production of an electric car and an internal combustion engine car differ quite a lot in favor of the internal combustion engine car. The emissions of an electric car are significantly higher than those of a comparable internal combustion engine car. According to one study, the production of a typical mid-size internal combustion engine car emits 9.2tCO_2 and similar type of electric vehicle production 14.6tCO_2 when NMC battery is used in EV [31]. So, according to this source, the electric car has about 59% higher emissions in manufacturing. Other studies support this result [32] which found a 57%

difference in emissions between the manufacturing of electric vehicles. The exact same result was found in a recent study by car manufacturer [33], which compared the life cycle carbon footprint of an internal combustion engine car and an electric XC40.

3.1.2 Battery production

Battery production is responsible for a large share of the emissions associated with the manufacturing of an electric vehicle. The high carbon footprint of production is due to the stages involved in the manufacturing process and where they are produced. In other words, what energy is used to make them. The main battery manufacturers are CATL, LG Energy Solution, Panasonic, Samsung, BYD Co. and SK innovation. These six biggest battery manufacturers were responsible for supplying 87% of batteries and battery metals for EVs in 2020 [34]. Most of these are in China, South Korea and Japan, i.e, countries where fossil powered energy generation dominate, like coal power. In battery manufacturing especially energy use is partially responsible for high emissions of production. Battery manufacturing demands very much energy, because of high temperatures during the process etc. which consumes a lot of energy [3].

The production of lithium-ion batteries emits around 61-106 kg of CO_2 per kWh capacity produced [35]. The emission range is wide, and it depends on the electricity used in production phase and production method used to produce batteries. These emissions are lower now compared to same study made in 2017 [36]. Emissions are lower mainly due to battery factories are running more efficiently now [35]. Emissions of battery production will most likely decline a substantial amount due to the grid decarbonization in the future [28]. These countries start to use more renewable energy production and other countries with less carbon intense electricity mix may start to manufacture batteries.

3.1.3 Emissions during usage

There are no direct in-use emissions from an electric car because it runs on electricity. However, during operation, the way in which the electricity is generated during charging must be considered. This is the only thing that affects the indirect emissions during operation of an electric vehicle. In an ideal situation, electric vehicles would be charged using only renewable energy sources, which would result in truly zero emissions during operation. However, this scenario is only marginally realized today. Therefore, it is necessary to estimate how much of the energy used in the electricity grid is produced by fossil methods. Table 4 shows the carbon intensity of electricity grids in three biggest markets in the world for EVs [37].

Table 4: Electricity production intensity in USA, Europe, and China.

Country	**Carbon intensity** gCO_2/kWh
USA	350 (2020)
Europe	225 (2020)
China	623 (2019)
World average	475 (2019)

China has the most intense electricity production and Europe has the least intense. Europe is the best of these three to charge EVs. It can be used to assess the purity of the electricity grid in different parts of the country and thus determine the in-use indirect emissions for electric vehicles. There are energy losses in transition from power plant to the outlet of an electric car so the losses must be taken to account. Powerplants in average are estimated to have 50% efficiency [38]. In addition, there are minor losses of transmission lines, local grid, transformers and inverter [39]. Total efficiency from power plant to the outlet of electric vehicle is 41%. This means that every 1kWh of charged energy to the battery needs 2.44kWh of energy production. With average of 0.2kWh/km energy consumption of EV it emits 231.7 gCO_2/km with world average electricity grid [40].

In the case of internal combustion engines, emissions are caused by tailpipe emissions during operation itself. In 2019, emissions from all new internal combustion engine cars averaged

122.3 gCO_2/km [41]. In real life, emissions are much higher than those reported by manufacturers. An example is the Volkswagen diesel gate scandal, where the cars they produced actually had emissions many times higher than those reported [42]. Real world consumption is 39% higher than claimed by manufacturers [43]. Real world data is used in this work to be as close to reality as possible. Increasing trend is that manufacturers claim emissions and fuel consumption to be unrealistically low. According to ICCT [43], the difference between real world data and official data have risen since 2012. This may be because car manufacturers must meet regulations of emissions, so they manipulate the test to get desired results.

In addition to tailpipe emissions, emissions from fuel production must also be considered. Emissions from petrol and diesel production must consider the manufacture of the product itself, any transport during manufacture and the transport of the final product to the petrol station. The emissions from the production of both petrol and diesel fuels consist of the extraction of the crude oil into the barrel and its transport to the refinery, and then the refining process itself. The refined product also must be transported to the desired location, such as a petrol station to be filled into cars.

Transport of only one barrel for refinery causes 63 kg of CO_2 emissions. Then the refining process itself. According to this [44] study, refineries in Europe contribute to emissions 10.2 CO_2eq/MJ for gasoline and for diesel 5.4, respectively. However, most of the processing takes place outside Europe, which suggests that the actual figure is probably higher. The transport from the refinery to the petrol station causes a relatively small increase in total emissions.

Total emissions from fuel production are 3140 gCO_2/litre and for diesel 3310 gCO_2/litre [44]. When these are added to normal fuel consumption and calculated at 7.2l/100km fuel consumption [25], that adds up to 393 gCO_2/km in total. As can be seen from this result, the production of fuel increases the using period emissions of ICE vehicle quite significantly, by ca. 135%.

4. Recycling

Recycling as part of the analysis and comparison of the life cycle carbon footprint of an electric vehicle is crucial. This section examines how well batteries, power electronics and other components of electric vehicles can be recycled today. It also looks at the prospects for future developments in recycling.

Whatever the vehicle's propulsion system, recycling at the end of its life is important, as cars contain a huge number of recoverable materials, and it is therefore important to recycle these materials efficiently. The main difference in recycling between internal combustion engines and electric cars is the battery of the electric car. In addition to the battery, an electric car has more electronics, such as battery management system and power electronics.

According to study made by Volvo [33], recycling process emissions of ICEV and EV are very similar, so that doesn’t make difference in lifetime emissions. However, EVs made in future will have smaller carbon footprint if the batteries are made from recycled materials.

4.1 Battery

Every year hundreds of tons of batteries and battery materials end up landfill. It means that massive amount of environmentally harmful substances such as nickel and lead slowly leach into the landfill soil with rainwater. From the soil, the substances slowly make their way to groundwater making it contaminated [45]. There is chance for huge waste problem with all the batteries coming from end-of-life EVs. That’s why in recycling phase, it is important that EV batteries end up proper disposal. This is also huge potential for valuable material stream returning back to the battery supply chain.

Recycling of batteries is still at early stage, and it is undeveloped due to low number of EVs in global car fleet It will become more feasible and cheaper as the industry grows. In battery production, about half of the emissions comes from material production. Recycled materials have lower carbon footprint than materials from virgin sources [28]. One problem for large scale recycling of li-ion batteries is the variety of battery cathode materials and structures. This makes the recycling process complex and expensive.

There is also option to use batteries for second life purposes rather than disassembling them to recycling. Batteries from EVs can also be used in second life purposes such as stationary storage applications supporting electricity grid. When the battery is removed from an electric vehicle after use, it usually has a of 75-80% of its original capacity left, so it is still fully usable for different applications. This further reduces the carbon footprint of the electric vehicle, as the emissions from battery production can be spread over a longer period of time for different uses [28].

4.2 Electronics

EVs contains a lot of electronics, and they contain different materials and metals. There are also critical labelled materials in electronics which are gold and neodymium. There is gold mass fraction mainly in embedded electronics ranging 0.2-6g/t, which is a lot. Neodymium is mainly found in electric motors and the mass fraction of neodymium can be around 300g/t [46]. Neodymium is used for example in permanent magnet motors, audio systems and computers.

Recyclable materials that are critical have huge potential to be reused, but there are still not any regulations for electronics recycling in Europe. End-of-life vehicle treatment remains without pre-shredder dismantling of electronics [46].

5. Results

In this section results of this research will be shown and discussed. Future of electric vehicles and internal combustion engine cars will be discussed. New battery technologies will be examined.

Results are clearly on side of EVs even though there are a bit of controversial studies and data available on this topic. Still, most of the results of studies are showing that EVs have smaller carbon footprint. Figure 4 depict the comparison of EV to ICEV in different scenarios and markets. There is average scenario calculated world average electricity mix, China scenario which is calculated China's electricity mix and scenario where electricity is produced renewable energy sources.

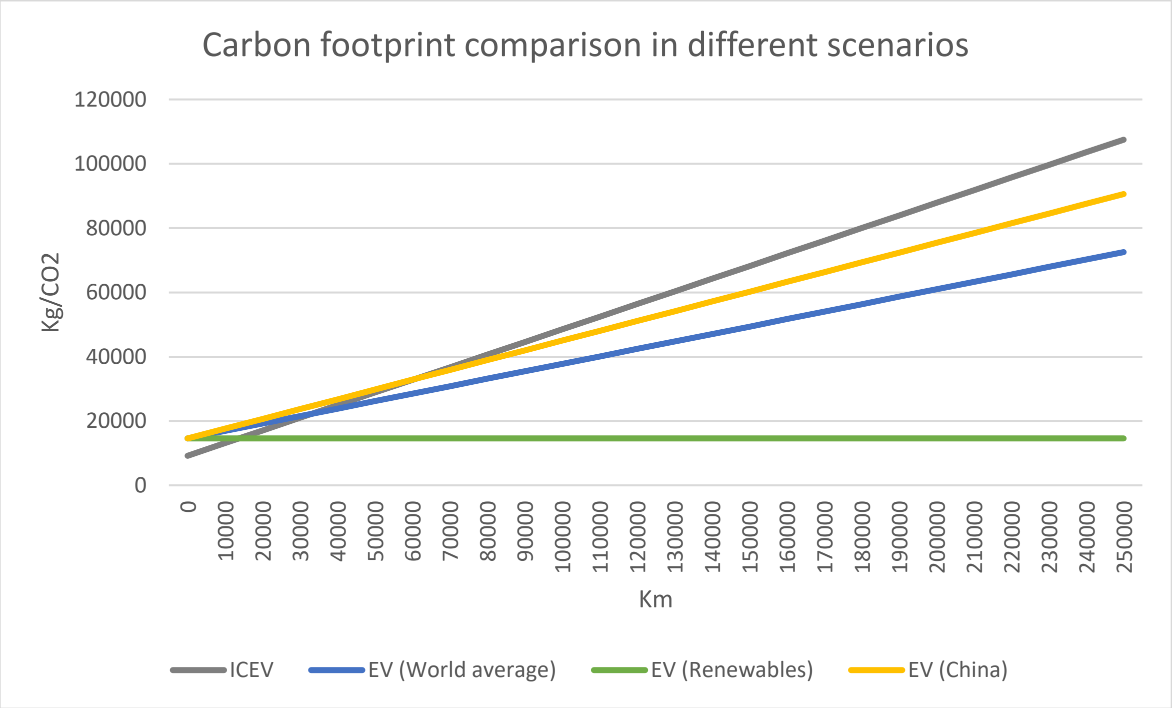

Figure 4. Carbon footprint comparison of ICEV an EV in different scenarios.

In Figure 4 we can see different scenarios compared. Calculations are made with starting point of production emissions. Starting point for EV is 14600kg of CO_2 and 9200 kg of CO_2 for ICEV. Emissions during use period that are 393.1 gCO_2/km for ICEV and 231.7 gCO_2/km for EV.

This shows that in all scenarios EV will eventually be less carbon intensive than ICEV. Worst case for EV is China because the electricity grid in China is the most carbon intensive of all the biggest markets. Despite of that EV still has smaller carbon footprint. Breakeven point in case China is at 60000 km. Breakeven point is that point when EV production emissions are compensated when comparing to ICEV.

World average case and renewables case are better for EV. Breakeven point in world average case is at 33000 km and in renewables case breakeven point is at 13000 km. With renewable energy sources the emissions during usage are true zero. This is the reason for very low breakeven point.

What can be said from these different cases is that even though production of EV is more carbon intensive, still using phase is the more significant factor in total carbon footprint. ICE vehicles emit carbon emissions so much during using phase that it doesn't make very big difference to breakeven point how EV is charged.

In average case according to these calculations, typical ICE car emits around 107.5 tonnes of carbon and EV 71.1 tonnes. This is, when assuming vehicles lifetime to be 250 000km. So full lifetime difference in carbon footprint is 36.4 tonnes on one car. This means almost 34% smaller footprint for EV. There are over 1 billion passenger cars travelling on the streets of the world today and if all of them would be replaced with EV, it would have a considerable reduction of carbon emissions globally [47].

5.1 Cost of emissions

Cost of emissions can be measured and compared in different methods. There is emission trading system (ETS) in Europe, and it is good way to evaluate cost of emissions. This system was established in 2005 to help reduce greenhouse gas emissions in a cost-effective and economic way. Allowances will be limited to a maximum level set by the EU, and companies will either receive or buy individual allowances. The cap will be reduced over time as the level of emissions gradually decreases. In this system, price for one ton of carbon emissions were around 93€ in February 2022 [48].

Cost of emissions in production phase with 9.2 tonnes of emissions for ICE vehicles is 855.6€ and for EV with 14.6 tonnes of emissions is 1357.8€. In production phase it is more cost effective to make vehicles with less emissions.

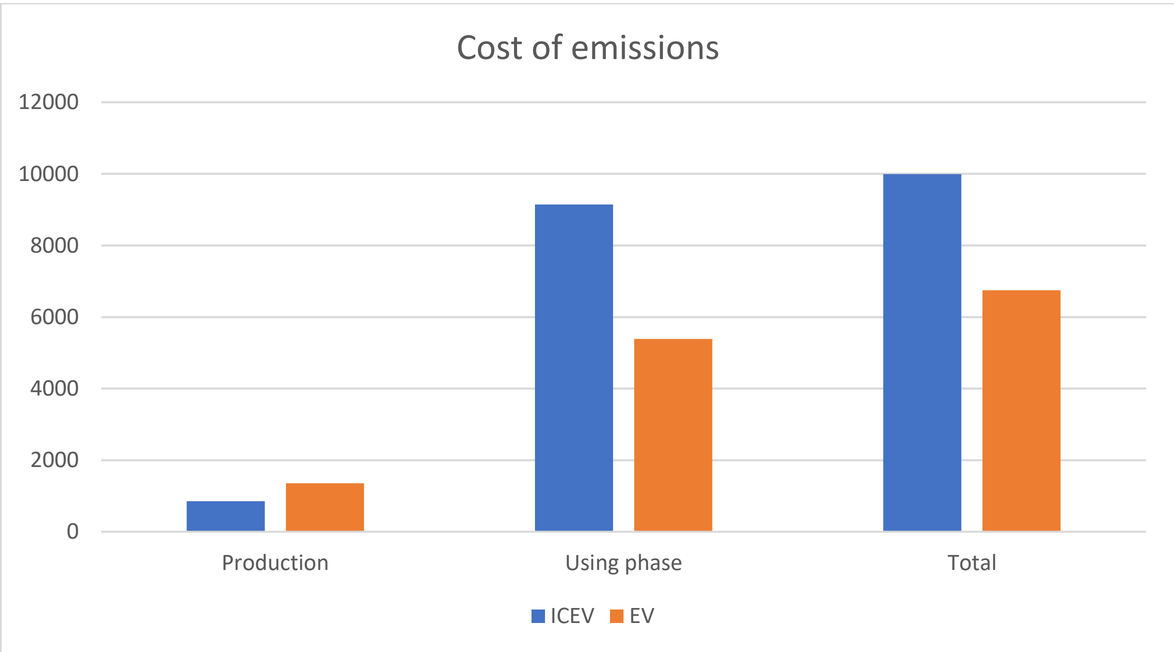

Figure 5. Cost of emissions comparison between EV and ICEV. Costs are divided in production and using phase. Assuming vehicle lifetime to be 250000 km

In Figure 5 are represented cost of emissions of both EV and ICEV. Most of the costs comes from using phase. There is significant difference in using phase costs of emissions in favour of EV. Total lifetime costs are also shown in Figure 5. Total costs for ICEV are 9994.7€ and 6745.3€ for EV.

5.2 Future outlook and discussion

It seems that future of EVs is bright. The destiny of ICE vehicles is still unknown. It looks like the big car maker are investing more into EV research and development and cutting from ICEV developing. Probably there will be improvements to internal combustion engine technology to reduce emissions, but eventually the ICE era will come to an end.

Commodity prices have started to go up due to supply chain issues in the world. High volume EV production could also lead to higher commodity prices which reflects to car production costs. It may lead to higher prices for car buyers also. If commodity prices keep getting more expensive, it may contribute to slowing down the electrification of transport, as car buyers are more likely to choose a cheaper second-hand internal combustion engine car than an expensive new electric car. Of course, second-hand electric cars are starting to appear on the market at a reasonable price, but still many people will not be able to buy one for a long time. To speed up the green transition, taxes on electric cars could be reduced and government subsidies could be provided to electric car buyers.

Lithium-ion battery technology is long established and new battery technologies are being developed. There has been a lot of talk recently about solid-state batteries being the future of electric vehicle batteries and it could be the next battery technology for EVs and other applications where battery is needed like smartphones and laptops. One company developing them, Quantum scape, is developing batteries specifically for electric vehicles. But they are still in a development process and a few years away to be used in EVs.

Key difference between solid-state and li-ion battery is that solid-state battery uses solid electrolyte while li-ion batteries use liquid electrolyte. Benefit from solid electrolyte is that solid-state batteries can have better energy density; in fact, they can pack in twice as much energy than li-ion batteries. These solid electrolytes aren't as reactive as liquid ones used in li-ion batteries. This leads to possible longer life span and solid-state batteries will not catch fire or explode, meaning they are safer product.

It is possible that some other technology will become better than electric vehicles. hydrogen technology could be one EV alternative right now, but hydrogen technology on car applications is very early stage and it is very hard to say could it be better option. Toyota is backing hydrogen technology and they are developing hydrogen cars. One problem with hydrogen cars is inefficiency, because energy must move from wire to gas to wire to power the car. But time will tell, if EVs are the final propulsion technology for transportation.

6. Conclusion

This research aimed to examine carbon footprint of fossil fuel car and electric car in different phases during vehicles life cycle. These results were analyzed and compared to each other.

It was observed that carbon footprint of an electric vehicle is noticeably smaller than comparable internal combustion engine vehicle. EVs have bigger carbon footprint in production mainly due to the carbon intensity of battery production, but most of vehicles carbon footprint comes from using phase and ICEVs have much larger carbon footprint in this phase. This is due to tailpipe emissions of the vehicle and fuel production emissions. EVs emissions during using phase depends on the electricity mix used to charge the car. Even charging EV with coal powered electricity, it is still better than ICEV. EVs best case scenario is when it is charged from renewable energy sources such as wind and solar power. In this case EV have true zero emissions.

End of life emissions are very similar between ICE vehicles and EVs [33]. Battery recycling is important to get valuable materials back to supply chain after use. Recycling batteries spreads the emissions to longer period of time, and it helps making EVs carbon footprint smaller. Also new car production becomes less carbon intensive since new materials does not have to be taken from virgin sources. Considering all factors of vehicles life cycle, electric vehicles are clearly better option than fossil fuel cars.

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