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Exploring the Viability of Electric Vehicles

Sustainable Transportation in Gävleborg

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Abstract

Curbing global emissions of greenhouse gases is one the biggest challenges of our age. To contain global warming to below 2°C, all sectors must reduce fossil dependency. Within the transport sector, responsible for about one fourth of all emissions, the quest for fossil free alternatives is well underway. Governments are enacting policies to encourage the population to move away from fossil-intensive diesel and gasoline cars. EU has endorsed a penalty for auto manufacturers selling new cars with average tailpipe CO_2 emissions of total car sales above 95 g CO_2/km. Sweden has declared an intention to be the first fossil neutral country by 2045 and to reduce emissions from domestic transportation, excluding aviation, by 70% until 2030, compared to 2010 levels. An alternative to conventional cars, also known as internal combustion engine vehicles (ICEV), is the electric vehicle (EV). With significantly lower greenhouse gas emissions, electric vehicles will play an essential part in the de-carbonization. Sweden now has over 100,000 EVs on the roads as compared to 15,000 in 2015, and the region of Gävleborg intends that 50% of new car sales should be zero tailpipe emission vehicles by 2025. However, only around 3% of new car sales in Gävleborg in 2019 are considered zero tailpipe emission vehicles.

This report aims to understand what arguments promote the adoption of EVs for companies in Gävleborg, and any potential drawbacks. The current state of electric vehicles and related infrastructure is investigated alongside policies intended to encourage electric transportation. Additionally, representatives from some of the electricity grid companies in Gävleborg were interviewed to understand the potential impact electric vehicles could have on the grid infrastructure. The environmental impact is also discussed coupled with difficulties performing an environmental assessment of EVs. The following research questions are posed:

- What is the current state of EV technology and EV charging infrastructure?
- What are the regional utilities' views on EV in relation to grid infrastructure?
- What policies promote EV adoption, and how do they affect the cost of ownership?
- What life cycle aspects are decisive for the environmental impact of EVs?

EVs can be separated into four categories: fuel cell electric vehicles (FCEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV), each with different qualities. FCEVs are the most distinct alternative, as fueling is neither from diesel, gasoline nor electricity. Instead, an FCEV uses hydrogen to power the electric motor, with zero tailpipe emissions. FCEV is a new technology, and as a consequence there are only two models available on the Swedish market, with the only fueling station in Gävleborg located in Sandviken. HEVs have a small electric motor, with no plug-in charging possibilities and can be compared with an efficient ICEV. PHEVs can be charged from the grid and have a bigger electric motor than HEVs but still with a limited range (<80 km). For short distance commuters, the PHEV can significantly reduce environmental impact and lower fuel costs compared to ICEVs. On longer distances it is more comparable to an HEV. With an energy efficiency of up to 95%, zero tailpipe emissions and a more mature technology and infrastructure compared to FCEVs, BEVs are currently the most prominent alternative to reduce emissions enough to reach regional and national targets. Common arguments against BEVs are a high purchase price, short travel range and long charging times. In the early days, this might have been true, but today technology has advanced enough to challenge ICEVs, in terms of range, cost, and performance (Gröna Bilister, 2019).

Although purchase prices are still high compared to diesel and gasoline cars, the Swedish bonus-malus system offers up to SEK 60,000 in bonus to low emission vehicles. Besides, malus penalizes vehicles with emissions above 95 g CO_2/km with increased taxes in the first three years. Also, since electric motors are around four times more efficient than conventional combustion engines, coupled with a low electricity price, BEV (and PHEV) owners enjoy lower fuel costs than ICEV drivers. A total cost of ownership model, accounting for all costs during the holding period, shows that EVs are cost-competitive to ICEVs already today, as illustrated in Table 1.

Table 1. Overview of the total cost of ownership, assuming 13,000 km per year

Cost (SEK)	BMW i3 (BEV)	VW Golf (ICEV)	Kia e-Niro (BEV)	VW Passat GTE (PHEV)	VW Passat SC (ICEV)
3 years (SEK)	204,630	215,730	243,340	277,640	239,360
6 years (SEK)	322,620	327,470	378,630	425,480	363,530
3 years (SEK / month)	5,680	5,990	6,760	7,700	6,650
6 years (SEK / month)	4,480	4,550	5,260	5,910	5,050

Another typical ownership model is the use of a company car for private purposes. The car is then considered a taxable benefit and the driver pays taxes on a benefit value determined by the Swedish Tax Agency (Skatteverket). The car is usually paid for by the company using a leasing option since the value-added tax (VAT) is reduced to 50% on company leasing deals. The Swedish government considers the benefit value comparable to an equivalent ICEV, to promote the use of alternatives to ICEVs. It offers a strong incentive as EVs are typically much more expensive than ICEVs. As an example, the monthly benefit value of a Volkswagen Passat GTE is 38% lower than for a Volkswagen Passat Sport Combi, although the initial purchase price is SEK 160,000 higher.

The range has increased over the years as a result of rapidly falling battery prices and improved energy density. Most battery electric vehicles available on the Swedish market have a range around or above 300 km. A range of 300 km is enough to cover 98 out of 100 trips made in Sweden by car (no charging needed). Additionally, the average daily driving distance for a car in Gävleborg is 32 km, meaning that even most PHEVs (in electric mode) could cover the daily needs on a single charge. New data suggest that car batteries will last at least 14 years, longer than the ten years previously expected. As a result the cars will maintain range performance better than anticipated, and the car will depreciate less in value. Research shows that already today, electric vehicles are depreciating more slowly than diesel and gasoline alternatives. It is also important to remember that a car battery's lifetime is considered to have reached end-of-life when 80% capacity remains. If drivers can accept lower capacity, the battery will have an even longer lifespan. Additionally, the batteries can be reused after end-of-life for other purposes, reducing the total environmental impact and increasing the residual value of the vehicle.

Charging is often distinguished in three categories: slow, semi-fast and fast charging. While chargers are predominately slow chargers, most are installed at home or at a workplace where cars are parked throughout either the day or night. At home or in the office, charging speeds become less relevant and it is estimated that up to 95% of charging takes place in these locations. Slow charging can be done without installing proper charging equipment. However, due to the risk of fire related to this kind of charging, the Electricity Safety Agency (Elsäkerhetsverket) urges everyone to install a dedicated wall box or charge point. To encourage charge point installations, the Swedish government is offering 50% or up to SEK 15,000 in subsidy per charging point for private charging installations. Public charging provides fast charging, and in certain places it is already possible to charge a car 30 times faster compared to slow chargers, reducing the charging time to 30 min or less for most vehicles. Potential car buyers should, however, check the car's specifications as not all models support the different charging speeds.

A massive uptake of electric vehicles could increase the stress on local electricity grids. If EV owners are allowed to charge at will it could cause network overloads, frequency deviations, and reduced power quality. A way of mitigating these problems is to use smart charging. The concept allows remote steering of charging points allowing grid operators, third-party actors or the owner to stop or reduce charging in times of high stress on the grid or short energy supply. The use of smart charging can not only improve the stability of the grid, but could also lower costs for EV owners. If vehicle-to-grid technology matures, it might even be possible to earn money by providing grid supporting services to the electricity company. However, grid companies in Gävleborg do not foresee any significant problems in the short term. Long-term concerns relate to grid congestion and power quality. Smart charging is discussed by all interviewees and anticipated to play a vital role in the future electricity infrastructure. If companies can avoid network upgrades, smart charging offers potential cost savings already today. Tariff structures are likely to change in the future, costing more money for high power consumption and increasing costs for energy during peak periods. Electricity consumers able to reduce peaks and shift demand to low-intensity periods will then possibly see reduced costs, increasing the potential of smart charging.

Reduction of environmental impact has always been the key argument for electromobility. However, there is some debate about to what extent. A method for evaluating environmental impact is to use life cycle assessment (LCA). An LCA can be used to compare different modes of transport or different fuels such as EVs and ICEVs. There are, however, varying results, ranging from only 10% to as much as a 50% reduction in greenhouse gas (GHG) emissions compared to diesel. Despite the varying conclusions, the scientific community is in accord; electric vehicles have a lower climate impact than conventional cars. The variations stem from varying assumptions about the lifetime of the batteries, electricity mix, energy density, driving patterns, weather conditions, and so on. The Swedish electricity mix, for example, has a considerable portion of hydro and nuclear power, and therefore low GHG emissions per kWh. For countries where electricity production is more dependent on coal and gas, the emissions during the use phase will be higher. This highlights the importance of developing renewable energy sources alongside the adoption of EVs, if climate targets are to be met. Despite the low emissions during the use phase, EVs in Sweden still have a considerable climate impact. Producing EV batteries is an energy-intensive process and most manufacturing facilities are outside of the EU, in for example Asia. As a result, a large portion of the GHG impact of EVs is accumulated even before the car is on the road. There is also a risk of impact shifting, from reducing greenhouse gases to increasing local toxicity for miners during mineral extraction, for example. It is therefore essential to take a life cycle perspective, rather than only looking at the use phase and battery production stage. One more life cycle phase warranting consideration is the end-of-life. Currently, recycling rates are low, causing environmental impacts as significant material resources are lost. As the technology matures, recycling and reuse will likely follow suit. The second life of batteries can reduce the significance of environmental impact caused by, for example, energy-intensive production. By using car batteries considered worn out by the auto industry in other applications such as grid support, the useful lifetime of batteries can be extended.

Overall, adopting EVs presents an opportunity to reduce GHG emissions in Gävleborg while phasing out gasoline and diesel fueled cars. Arguments of high price, range and long charging times have diminished as the technology has matured and as government policies offer significant cost reductions. With few drawbacks and based on the current state, the authors recommend that EV adoption should be increased in the coming years. Heavy transport and hydrogen infrastructure are not assessed in this electromobility report. Heavy transportation might not be as suitable for battery technology due to the substantial mass of the batteries. An alternative technique is fuel cell–based heavy transportation. This concept will be studied in an upcoming report.

Keywords: electric vehicle, electromobility, sustainable transport, batteries, electricity grid

Sammanfattning

Att minska globala utsläpp av växthusgaser är en av vår tids största utmaningar. För att begränsa jordens uppvärmning till under 2 °C måste alla sektorer minska sitt beroende av fossila bränslen och inom transportsektorn, som står för en fjärdedel av utsläppen, är jakten efter fossilfria alternativ i full gång. Olika länders regeringar antar riktlinjer för att uppmuntra medborgare att byta ut fossilintensiva diesel- och bensinbilar. EU har godkänt en lag som bötfäller biltillverkare som säljer nya bilar med ett genomsnittligt CO_2-utsläpp över 95 g CO_2/km, baserad på tillverkarens totala årsförsäljning. Sverige har som målsättning att bli det första fossilneutrala landet år 2045 och att minska utsläppen från inrikes transporter, exklusive flyg, med 70 % fram till 2030, jämfört med 2010 års nivåer. Ett alternativ till konventionella bilar, alltså förbränningsmotorfordon (ICEV), är elfordon (EV). Med betydligt lägre utsläpp av växthusgaser spelar elfordon en viktig roll i minskningen av koldioxidutsläppen. Sverige har nu över 100 000 elfordon på vägarna jämfört med 15 000 år 2015, och regionen Gävleborg avser att 50 % av nybilsförsäljningen ska vara nollutsläppsfordon 2025. Men endast cirka 3 % av nybilsförsäljningen i Gävleborg under 2019 var nollutsläppsfordon.

Syftet med rapporten är att förstå vilka skäl som främjar att företag i Gävleborg skaffar elfordon och vad som motverkar detta. Det aktuella tillståndet för elfordon och tillhörande infrastruktur undersöks tillsammans med styrmedel som syftar till att uppmuntra elektrifiering av transporter. Dessutom har representanter från några av Gävleborgs elnätsföretag intervjuats för att förstå den potentiella inverkan som elfordon kan ha på nätinfrastrukturen. Miljöpåverkan diskuteras också i kombination med svårigheter att utföra en miljömässig bedömning av EV. Följande forskningsfrågor ställs:

- Vad är situationen för dagens elfordonsteknik och laddinfrastruktur?
- Vad är de regionala nätföretagens syn på elfordon i förhållande till nätinfrastruktur?
- Vilka styrmedel främjar anskaffning av elfordon och hur påverkar de ägandekostnaderna?
- Vilka livscykelaspekter är avgörande för elbilens miljöpåverkan?

EV kan delas upp i fyra kategorier: bränslecellsfordon (FCEV), hybridfordon (HEV), laddhybridfordon (PHEV) och batterifordon (BEV), var och en med olika kvaliteter. FCEV är ett intressant alternativ eftersom bränslet varken kommer från diesel, bensin eller el. Istället använder ett bränslecellsfordon vätgas för att driva elmotorn vilket resulterar i nollutsläpp från avgasröret. FCEV är en ny teknik och som en konsekvens finns det bara två modeller tillgängliga på den svenska marknaden, med en enda bränslestation i Gävleborg nämligen i Sandviken. HEV har en liten elmotor utan laddningsmöjligheter via nätanslutning och kan jämföras med en effektiv ICEV. PHEV kan laddas via elnätet och har en större elmotor än HEV men med en begränsad räckvidd (< 80 km). För kortavståndspendlare kan PHEV minska miljöpåverkan avsevärt och sänka bränslekostnaderna jämfört med ICEV. På längre avstånd är den mer jämlik med en HEV. BEV har en energieffektivitet på upp till 95 %, noll avgasutsläpp och en mer etablerad teknik och infrastruktur än FCEV. BEV är för närvarande det mest framstående alternativet för att minska utsläppen tillräckligt för att nå regionala och nationella mål. Vanliga argument mot BEV är ett högt inköpspris, kort räckvidd och långa laddningstider. Det må ha varit så tidigare, men idag har tekniken utvecklats tillräckligt för att utmana ICEV, gällande räckvidd, kostnad och prestanda (Gröna Bilister, 2019).

Även om inköpspriset fortfarande är relativt högt jämfört med diesel- och bensinbilar, erbjuder det svenska bonus-malus-systemet upp till 60 000 SEK i bonus för bilar med låga utsläpp. Dessutom straffas fordon med utsläpp över 95 g CO_2/km p.g.a. malus-systemet med höjd skatt de första tre åren. Eftersom elmotorer är ungefär fyra gånger effektivare än konventionella förbränningsmotorer, tillsammans med ett lågt elpris, har BEV-ägare (och PHEV-ägare) lägre bränslekostnader än ICEV-ägare. En total ägandekostnadsmodell som redovisar alla kostnader under ägandetiden visar att EV är kostnadsmässigt konkurrenskraftiga mot ICEV redan idag, vilket visas i Tabell 1.

Tabell 1. Översikt av den totala ägandekostnaden med 13 000 km/år antaget.

Kostnad (SEK)	BMW i3 (BEV)	VW Golf (ICEV)	Kia e-Niro (BEV)	VW Passat GTE (PHEV)	VW Passat SC (ICEV)
3 år (SEK)	204,630	215,730	243,340	277,640	239,360
6 år (SEK)	322,620	327,470	378,630	425,480	363,530
3 år (SEK/månad)	5,680	5,990	6,760	7,700	6,650
6 år (SEK/månad)	4,480	4,550	5,260	5,910	5,050

En typisk ägarmodell är företagsbil för privata ändamål, så kallad förmånsbil. Bilen betraktas då som en beskattningsbar förmån och föraren betalar förmånsskatt på ett värde som fastställts av Skatteverket. Bilen betalas vanligtvis av företaget via ett leasingalternativ eftersom momsen reduceras till 50 % via företagets leasingavtal. Dessutom avser svenska staten främja alternativa drivmedel genom att sänka förmånsvärdet på miljöbilar, till ett värde motsvarande en jämförbar ICEV. Detta ger ett starkt incitament för EV som vanligtvis är mycket dyrare än ICEV. Som ett exempel är förmånsvärdet per månad för en Volkswagen Passat GTE 38 % lägre än för en Volkswagen Passat Sport Combi, även om det ursprungliga inköpspriset är 160 000 SEK högre.

Räckvidden har ökat under åren till följd av snabbt fallande batteripriser och förbättrad energitäthet. De flesta elektriska batteribilar på den svenska marknaden har en räckvidd på cirka 300 km eller längre. En räckvidd på 300 km räcker för att täcka 98 av 100 resor i Sverige med bil (på en laddning). Dessutom är den dagliga genomsnittliga körsträckan för en bil i Gävleborg 32 km, vilket innebär att även de flesta PHEV (i el-läge) kan täcka de dagliga behoven på en enda laddning. Nya uppgifter tyder på att bilbatterier kommer att hålla minst 14 år, längre än de tio år som bedömts tidigare. Som ett resultat kommer bilarna att bibehålla räckvidden bättre än förväntat, och bilens värde kommer att minska långsammare. Forskning visar att redan i dag minskar elfordonets värde långsammare än diesel- och bensinalternativ. Det är också viktigt att påpeka att bilbatteriets livslängd anses ha nått sin fulla livslängd när det återstår 80 % kapacitet. Om förare kan acceptera lägre kapacitet har batteriet en ännu längre livslängd. Dessutom kan batterierna återanvändas efter den första livscykeln för andra ändamål, vilket minskar den totala miljöpåverkan och ökar fordonets restvärde.

Laddningshastigheten kan delas upp i tre kategorier: långsam, semi-snabb och snabbladdning. Laddare är huvudsakligen långsamma laddare och installeras mest hemma eller på arbetsplatsen där bilar parkeras under antingen hela dagen eller natten. Hemma och på arbetsplatsen blir laddningshastigheten mindre relevant och det uppskattas att upp till 95 % av laddning sker på dessa platser. Långsam laddning kan göras utan att installera regelrätt laddningsutrustning, men på grund av brandrisk i samband med denna typ av laddning uppmanar dock Elsäkerhetsverket alla att installera en särskild laddstolpe eller laddplats. För att uppmuntra installation av laddplatser erbjuder den svenska regeringen 50 % (upp till 15 000 SEK) i subvention per laddplats för privata laddningsanläggningar. Offentlig laddning erbjuder snabbladdning, och på vissa platser är det redan möjligt att ladda en bil 30 gånger snabbare jämfört med långsam laddning, vilket minskar laddningstiden till 30 minuter eller mindre för de flesta fordon. Framtida bilköpare bör dock kontrollera bilens specifikationer eftersom inte alla modeller stöder samtliga laddningshastigheter.

En kraftig ökning av antalet elfordon kan öka belastningen på de lokala elnäten. Om EV-ägare får ladda på eget bevåg kan detta orsaka överbelastningar i näten och försämrad frekvens- och effektkvalité. Ett sätt att mildra dessa problem är att använda smart laddning. Konceptet tillåter fjärrstyrning av laddningspunkter som gör det möjligt för nätoperatörer, tredjepartsaktörer eller ägaren att stoppa eller minska laddningen i tider med hög belastning på nätet eller låg energitillförsel. Användningen av smart laddning kan inte bara förbättra stabiliteten i nätet utan kan också sänka kostnaderna för EV-ägare. Om tekniken för ”el från fordon till nätet” (”vehicle-to-grid”) mognar kan det till och med vara möjligt att tjäna pengar genom att tillhandahålla nätstödstjänster till elföretaget. Nätföretagen i Gävleborg förutser dock inga betydande svårigheter på kort sikt. Problem på lång sikt är kopplade till överbelastning och elkvalité. Smart laddning diskuteras av alla intervjuade och förväntas spela en viktig roll i den framtida el-infrastrukturen. Om företag kan undvika uppgraderingar av nätet, erbjuder smart laddning möjliga kostnadsbesparingar redan idag. Kostnadsstrukturer förändras sannolikt i framtiden och det är troligt att det kommer att kosta mer för stora effektuttag och för energi vid hög belastning. Elkonsumenter som kan minska topparna och flytta efterfrågan till lågintensitetsperioder kommer då möjligen att få lägre kostnader, vilket ökar potentialen för smart laddning.

Minskad miljöpåverkan har alltid varit det viktigaste argumentet för elektromobilitet, men det debatteras i vilken utsträckning minskningen sker. En metod för att utvärdera miljöpåverkan är att använda livscykelanalys (LCA). En LCA kan användas för att jämföra olika transportsätt eller olika bränslen som EV och ICEV. Det finns dock skiftande resultat, från endast 10 % till så mycket som 50 % minskning av växthusgasutsläpp jämfört med diesel. Trots de varierande slutsatserna finns en enighet i vetenskapssamhället; elektriska fordon har en lägre klimatpåverkan än konventionella bilar. Variationerna härrör från olika antaganden om batteriernas livslängd, elmix, energitäthet, körmönster, väderförhållanden och så vidare. Den svenska elmixen består mestadels av vatten- och kärnkraft och har därför låga växthusutsläpp per kWh. För länder där elproduktionen är mer kol- och gasbaserad kommer utsläppen under användningsfasen att vara högre. Detta åskådliggör vikten av att utveckla förnybara energikällor tillsammans med en ökning av antalet EV för att kunna uppnå klimatmålen. Trots de låga utsläppen under användningsfasen i Sverige har EV fortfarande en betydande klimatpåverkan. Att producera EV-batterier är en energikrävande process och de flesta produktionsanläggningar finns utanför EU, till exempel i Asien. Detta leder till att en stor del av växthusgas-påverkan från EV ackumuleras redan innan bilen är på vägen. Det finns också en risk för förflyttning av miljöpåverkan, från minskade växthusgaser till ökad lokal giftighet för gruvarbetare vid mineralutvinning. Det är därför mycket viktigt att ha ett livscykelperspektiv, och inte bara titta på användningsfasen och batteriproduktionsstadiet. Sluthanteringen av EV är ytterligare en livscykelfas som motiverar ett livscykelperspektiv. För närvarande är återvinningsgraden mycket låg, vilket orsakar miljöpåverkan eftersom betydande materialresurser går förlorade. När tekniken mognar kommer återvinning och återanvändning troligen att följa efter. ”Ett andra liv” för batterierna kan minska betydelsen av miljöpåverkan orsakad av till exempel energiintensiv produktion. Genom att använda bilbatterier, som av bilindustrin anses vara förbrukade, i andra applikationer som nätstöd, kan batteriets användbara livslängd förlängas.

Sammanfattningsvis, införande av EV ger möjlighet att minska utsläppen av växthusgaser i Gävleborg samtidigt som man avvecklar bensin- och dieselbränslen. Motargument så som högt pris, kort räckvidd och långa laddningstider har minskat i betydelse samtidigt som tekniken har mognat och strymedel erbjuder betydande kostnadsminskningar. Med få nackdelar och baserat på dagens situation rekommenderar författarna att införandet av EV bör ökas under de kommande åren. Tunga transporter och vätgasinfrastruktur bedöms inte i denna rapport om elektromobilitet. Batteriteknologi är troligen inte lika lämplig för tunga transporter på grund av batteriets höga vikt. En alternativ teknik är bränslecellsbaserade tunga transporter. Detta koncept kommer att studeras i en kommande rapport.

Nyckelord: elektriska fordon, elektromobilitet, hållbara transporter, batterier, elnät

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1 Introduction

If global warming cannot be held below 2°C, the planet will likely suffer consequences that threaten our modern civilization beyond repair (Ripple, Wolf, Newsome, Barnard, & Moomaw, 2019). Scientists are warning that the current efforts to reduce greenhouse gas (GHG) emissions are still a long ways off (Ripple et al., 2019). In total, 195 countries have signed the Paris climate agreement, creating a framework for keeping global temperature rise below 2°C and if possible, even below 1.5°C (United Nations, 2015). The transportation sector is a key contributor to European GHG emissions.

European Union (EU) policies include a target of at least 14% renewable fuels by 2030, and progressively decreasing average tailpipe emissions for new cars. The limit was introduced the first time in 2015 at 130 g CO_2/km, and since January 1, 2020, the EU fleet-wide average emissions target for new cars is 95 g CO_2/km (European Commission, n.d.-b). Manufacturers that exceed this limit, on their average sales, will be penalized and the fines can be high. Based on 2018 statistics, automakers would overshoot the limit by almost 25 g CO_2/km, resulting in total fines of around SEK 336 billion (336,000,000,000) in 2021 (Muñoz, 2019). The risk of high penalties should encourage carmakers to intensify production and sales of low emission vehicles. It should be noted that the target is an average of car sales by the manufacturer; hence, high emission cars can be offset by low emission cars.

With an ambitious goal of becoming the world's first fossil-free country, the Swedish Parliament agreed in June 2017 that Sweden should reach net-zero in terms of GHG emissions by 2045 (Prop 2016/17:146). As a step towards this goal, the domestic transport sector (excluding aviation) should reduce GHG emissions by 70% until 2030 compared to 2010 (Svenska Trafikutskottet, 2018). The Swedish Energy Agency recently concluded that to be able to reach this target, 16% of all Swedish vehicles need to be electric in combination with all gasoline and diesel fuels based on at least 60% renewable sources (Energimyndigheten, 2019).

In line with Ripple et al. (2019), the Gävleborg County Administrative Board (Länsstyrelsen) has identified that current efforts are likely not enough to avert climate collapse. They have therefore set a more ambitious target, compared to the Swedish government, of reaching climate neutrality already by 2035. With around 42% of regional GHG emissions generated by the transport sector, the County Administrative Board and Region Gävleborg have outlined the following transportation targets (Länstyrelsen, 2019):

- The vehicle fleet of all public actors in Gävleborg should be fossil-free by 2025.
- By 2025, 50% of new car sales in the region should be zero tailpipe emission vehicles.
- By 2025, 40% of all fuel consumption should come from renewable sources, with an increase of locally produced renewable fuels.
- At least 25% of personal transport should be done by public transport, walking or biking by 2025.

The battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) offer exciting alternatives to conventional cars. With zero tailpipe emissions during use, the BEV can both potentially reduce overall climate impact and significantly reduce pollutant emissions. Despite a limited electric range (< 70 km), PHEVs can reduce emissions during the use phase, compared to conventional cars. PHEVs can be particularly beneficial for short-distance commuters. With a daily commute shorter than the available range, all regular trips can be made on electricity only. Both options, grouped as electric vehicles (EVs), will play a crucial role in reaching international, national and regional emission targets. They will also reduce the need for biofuels when fossil fuels are abandonded to a more considerable extent.

Growing environmental concerns, falling car prices, and government incentives are paving the way for EVs in Sweden. Between 2015 and 2019, the Swedish EV fleet has grown from almost 15,000 to around 100,000 (Elbilsstatistik, 2020). Since the introduction of the new bonus-malus system, providing a discount for low-emission vehicles, the number of EVs on the road has grown more than 50% (Elbilsstatistik, 2020). However, perceptions about cost, range and overall performance still act as a preserved barrier for EV adoption (Coffman, Bernstein, & Wee, 2017; Saldaña, Martin, Zamora, Asensio, & Oñederra, 2019; Sandén, 2017). The overarching goal of this report is to support regional small and medium-sized enterprises (SME) in their sustainability efforts regarding transportation. The purpose, therefore, is to present what arguments currently promote the adoption of EVs in Gävleborg and any potential drawbacks. In support of this purpose, the following research questions are answered:

- What is the current state of EV technology and EV charging infrastructure?
- What are the regional utilities' views on EV adoption in relation to grid infrastructure?
- What policies promote EV adoption, and how do they affect the cost of ownership?
- What life cycle aspects are decisive for the environmental impact of EVs?

With companies making up around two-thirds of new car purchases (Bil Sweden, 2020), business procurement decisions will significantly impact regional and national emission reductions. Companies such as charging solutions suppliers, will also play an important role in decarbonizing the transport sector, as local grid companies expect private actors to build out and maintain the necessary charging infrastructure[1]. While SMEs are the target group for this report, the information made available here will suit anyone interested in sustainable transportation and electromobility.

Electromobility can be defined as a "road transport system based on vehicles that are propelled by electricity" (Sandén, 2017). Road transportation includes cars, motorbikes, buses, heavy and light trucks, bicycles, and scooters, and the concept is rapidly expanding. In this report, electric cars charged by grid electricity are in focus. Car travel in Gävleborg is of concern since it is the cause of 62% of Gävleborg's road GHG emissions (Länstyrelsen, 2019). Hybrid electric vehicles (HEV) are mentioned in the report, but they are non-plug-in vehicles and not "propelled by electricity" from the grid, and are therefore not in focus. Excluded from this report are heavy transport and hydrogen infrastructure, which will be the focus of an upcoming study.

This report is structured as follows. Chapter 1 provides a brief overview of the challenges of sustainable transport, and the aim and research questions to be answered. Description of how this study has been conducted and the methods used are presented in chapter 2. Chapter 3 highlights the EV performance and describes the battery technology, while chapter 4 provides insights into charging technology and infrastructure. Chapter 5 puts forward the potential impact EVs can have on the electricity grid, including results from the interviews. Chapter 6 presents policies, incentives, and costs concerning EVs, while chapter 7 focuses on the life cycle and environmental aspects of EVs. Finally, in chapter 8, the findings in this report are discussed, the research questions are answered, and in the end, concluding remarks and encouragements for future work are presented.

[1] Hans Ädel and Teddy Hjelm (Gävle Energi); Mikael Palm (Sandviken Energi); Mikael Halvarsson (Ljusdal Energi).

2 Method

The methods used in this study are literature review and interviews. Literature references are mainly scientific, either from peer-reviewed scientific papers or from research reports. Google Scholar is the most prominently used search engine, while articles have been retrieved from publishers like Elsevier and Springer, and databases like ResearchGate. Although some search keywords related to EV have been used, the most common method to find relevant articles has been snowballing, both backwards and forwards. Other literature references include newspaper articles and government reports, regulations, statistic databases, and company websites. Information from these sources have been found either through personal referral or Google search.

The purpose of the interviews was to understand how a significant uptake of EVs might affect the local and regional grids in Gävleborg and assess utilities' readiness to mitigate any potential risks. All interviews have been conducted in Swedish, and any quotes used in this report have been translated into English. The interviews can be considered semi-structured with questions prepared and sent out to the interviewees before the meeting. These questions provided the foundation, and additional questions have been introduced for clarification. The focus has been on the following topics:

- Challenges and opportunities concerning electromobility and grid infrastructure
- Grid strategies for electric vehicles and charging
- The role of the grid operator concerning electromobility

Six people from four grid companies out of ten in Gävleborg were interviewed (see Table). Where information from the interviews has been used, references are added as footnotes. All interviewees were allowed to read and if necessary comment and revise quotes before the publication of this report.

Table 2. The associated companies of the interviewees including their role and the date the interview was conducted

Name	Company	Role	Interview Date
Anders Holmsten	Gävle Energi	Manager, energy services	2019-11-21
Hans Ädel	Gävle Energi	Manager, grid infrastructure	2019-10-30
Jonas Sunryd	Ellevio	Strategy and Business developer & New business	2019-10-24
Lennie Jonsson	Sandviken Energi	Manager, grid planning	2019-11-20
Michael Halvarsson	Ljusdal Energi	Grid manager	2019-10-31
Mikael Palm	Sandviken Energi	Business developer, charge infrastructure roll-out	2019-10-22
Teddy Hjelm	Gävle Energi	Grid strategist	2019-10-30

3 Electric Vehicle Performance and Battery Technology

Electric cars have evolved since the inception and there are different variations of EVs. Performance, including range, energy efficiency and safety has improved alongside battery technology and lifespan.

3.1 Electric Vehicles

There are four categories of EVs: battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), and fuel cell electric vehicle (FCEV).

Battery Electric Vehicles

Unlike conventional cars, also referred to as internal combustion engine vehicles (ICEV), BEVs have a fully electric drive train, producing zero tailpipe emissions. The electric motors operate at an efficiency of 80–95% (Canals Casals, Martinez-Laserna, Amante García, & Nieto, 2016), making it an attractive alternative compared to internal combustion engines (ICE), typically operating below 20% (Åhman, 2001). The main drawback of BEVs, besides a high purchase price, is their limited driving range compared to ICEVs, ranging from around 150 km (for a small city car) to about 600 km (Tesla Motors, 2020). Additionally, an electric car can, depending on the charger, take between 0.5 – 8 hours to charge compared with a few minutes for filling up the fuel tank of an ICEV. Although BEVs have a high purchase price, they have low maintenance costs and significantly lower fuel costs than ICEVs.

Sales of BEVs in Gävleborg have seen a significant increase since the introduction of the bonus-malus system and is currently at 3.2% (compared to 0.6% in 2017). It is still, however, below the national average of 4.3% (Trafikanalys, 2020). The three most sold BEVs in Sweden in the past month (as of late February 2020) are Kia e-Niro, Renault Zoe and Tesla Model S (Elbilsstatistik, 2020) and there are currently 35 BEV models available for sale on the Swedish market (Teknikens Värld, 2019). Still, only 0.4% of all the cars in Gävleborg and 0.6% in Sweden are BEVs (Trafikanalys, 2020).

Plug-In Hybrid Electric Vehicles

A plug-in hybrid electric vehicle (PHEV) is a combination of a BEV and an ICEV with both an electric motor and an ICE and typically has an electric range of 30 – 80 km. The PHEV can generally operate in two distinct modes (or in variations of these), charge-depleting or charge-sustaining mode. The first allows the driver to consume only electric power until the battery is depleted, and the second mode combines the electric motor and combustion engine to optimize the driving range (Poullikkas, 2015). Between the two, for a commuter with battery charging access at work, it would make sense to use charge-depleting mode, minimizing the use of fossil fuels and CO_2 emissions. Regardless of mode, PHEVs emit much less GHG emissions during the use phase under normal driving conditions than comparably sized ICEVs.

PHEVs are less popular among new car registrations than BEVs. In Gävleborg the average sales of PHEVs is 2.7% compared to 3.2% sales of BEVs. PHEVs in Gävleborg are also lower than the Swedish sales average of 6.8% PHEVs. Overall, only 0.5% of all the cars in Gävleborg and 1.4% of all the cars in Sweden are PHEVs (Trafikanalys, 2020). There are 41 PHEV models available on the Swedish market (Teknikens Värld, 2019), and the three most sold are currently Kia Optima PHEV, Volkswagen Passat GTE, and Mitsubishi Outlander PHEV (Elbilsstatistik, 2020).

Hybrid Electric Vehicle

Like the PHEV, the HEV has dual motors, one electric and one ICE. Unlike the other EVs, it cannot charge from the grid. Instead, the electricity comes from the ICE and from regenerative breaking, offering a better fuel economy than its ICEV counterparts. With a small electric motor, it is almost always used simultaneously with the ICE. It is rarely either-or. Due to not being plug-in electric vehicles and the limited electric range, HEVs are not in focus in this report.

Despite generally not being eligible for a purchase premium through bonus-malus, HEVs are the most popular EVs in Gävleborg. In 2019 over 12% of new car registrations were HEVs, compared to a national average of 9% (Trafikanalys, 2020). The popularity probably stems from comparable purchase prices to ICEVs, the better fuel economy (than for ICEVs), and that most models are exempt from the malus penalty (emissions lower than 95 g CO_2/km).

Fuel Cell Electric Vehicle

Like the BEV, an FCEV only has an electric motor and is based on similar technology. The main difference is the fuel cells, which run on hydrogen gas. Unlike BEV and PHEV, FCEVs cannot charge from the electricity grid but require specific hydrogen gas pumps. The limited availability of hydrogen fueling stations is currently a drawback. However, without a big battery, the car is lighter, and one can expect to travel at least 500 km per tank. Currently, there are only two FCEVs, Toyota Mirai and Hyundai Nexo, available on the Swedish market (Teknikens Värld, 2019), which helps explain why there are fewer than 0.01% FCEVs on Swedish roads. In Gävleborg, there are only 14 FCEVs (Trafikanalys, 2020), all part of Sandviken municipality vehicle fleet[2]. Sandviken is also one of only four cities in Sweden where it is possible to fuel a hydrogen car (Johan Juhlin, 2019). FCEVs are not in focus in this report.

3.2 Performance

Range

One of the main reasons people are reluctant to buy a BEV is the perceived shorter range. While a short range was accurate in the early years of EVs, the best models available on the market now boast a range of about 600 km. A larger battery size plays a significant part but also the higher energy density of the battery. Even with a shorter range than ICEVs and PHEV, new BEVs can provide enough range for most trips. The average daily driving distance per car in Gävleborg is only 32 km (Region Gävleborg, 2019), and 98% of all car trips in Sweden are shorter than 300 km (Liu, Wu, Christensen, Rautiainen, & Xue, 2015). One review states that "Kia e-Niro has such a long-range and fast charging that almost no one can disregard electric vehicles anymore" (Gröna Bilister, 2019). Table 1 shows an overview regarding battery electric range, size, and electricity consumption of some of the common EVs. The data is based on information found on the manufacturers' websites.

Table 1. Overview of electric range, battery size and electricity consumption for common EVs, data collected from the respective manufacturer's website

Model	Type	Electric range (km)	Battery size (kWh)	Electricity consumption (kWh / 100 km)
Tesla Model 3 long range	BEV	560	78	16
Kia e-Niro Advance	BEV	409	64	16
BMW i3	BEV	296	33	16.5
Nissan Leaf	BEV	270	40	20.6
Volkswagen Passat GTE	PHEV	56	13	14.7
Mitsubishi Outlander	PHEV	45	13.8	16.9

The potentially colder climate of Nordic countries and Gävleborg challenges the use of EVs in many ways, such as challenges identified in the RekkEVidde study (Laurikko, Granström, & Haakana, 2012). Cold weather and adverse road conditions increase driving resistances, and heating and ventilation consume high amounts of prime battery energy; this could lead to a shorter range. Additionally, cold weather necessitates slower charging and battery warming. In the following section, the impact on energy efficiency due to the colder climate is described.

Energy Efficiency of Vehicles

Energy efficiency can be defined as the percentage of total energy input to a machine or piece of equipment that is consumed in useful work and not wasted as useless heat. ICEVs have low energy efficiency and waste around 80% as heat. Conversely BEVs can expect at least 80% useful work and have a high energy efficiency (Poullikkas, 2015). During tests in optimal driving conditions, a

[2] Mikael Palm (Sandviken Energi).

Nissan Leaf has even measured as high as 97% efficiency with only minimal amounts of heat loss (Sandén, 2017).

Besides small heat losses, EV energy efficiency is attributed to regenerative braking. When the car slows down, the deceleration generates electricity to be stored in the battery. For BEVs, energy recovery can be as high as 19% (Rangaraju, De Vroey, Messagie, Mertens, & Van Mierlo, 2015).

However, a consequence of having almost no heat loss from the electric motor is that EVs need to supply more power to the air-conditioning system. Rangaraju et al. (2015) further conclude that battery thermal management and space heating consumes about one-third of total energy spent. In colder climates, the energy efficiency will, therefore, go down. The range can be increased by preheating the parked car using an interior heater, drawing power from the grid instead of the EV battery. New research suggests that improved heater technology can reduce the energy requirements by up to 50% for EVs in winter conditions compared to traditional heating systems (Hanley, 2018).

Due to the low efficiency of the hydrogen process, FCEV energy efficiency is only slightly better than ICEVs. While PHEV has a higher efficiency than ICEV, it is difficult to precisely determine by how much, as it depends on the ratio between the electric motor and ICE while driving, which is a consequence of driving patterns and behaviors (Gordon Strömfelt, Gröna Bilister, personal communication, March 5th 2020).

Safety

One of the main concerns regarding EV safety is the risk of fire. The lithium-ion chemistry is highly flammable, and battery fire could cause the release of toxic gases. Research and empirical data suggest, however, that EVs are significantly less likely to burst into flames than an ICEV (Sandén, 2017). Erik Söderholm (Söderholm, 2019) even argues that a standard interior heater might be more likely to cause a fire than an EV battery. Nevertheless, the technology is still new, and fire departments and first responders must learn to handle lithium-ion battery fires, to reduce the risk of, for example, toxic inhalation (Bisschop, Willstrand, Amon, & Rosengren, 2019).

3.3 Battery Technology

Small lead-acid batteries have been present in cars for over 100 years (Sandén, 2017), but despite the maturity of the technology, it has a low energy density. Therefore, the high energy density lithium-based chemistries are dominating the EV market (Romare & Dahllöf, 2017). The technology for cars is still new, and energy densities in lithium-ion batteries have increased by 50%, from 100 Wh/kg to 150 Wh/kg in the last decade alone. The increased energy density is crucial as the battery makes up more than 20% of the EV mass. Range performance is no longer an energy density issue but rather a question of cost (Nykvist, Sprei, & Nilsson, 2019).

There are three primary battery chemistries in use today. While lithium-ion phosphate (LFP) is favored by the Chinese government, everywhere else, manufacturers use some combination of lithium, cobalt, and nickel. Where Tesla has opted for lithium nickel cobalt aluminum oxide (NCA), all other manufacturers use lithium nickel manganese cobalt oxide (NMC) (Romare & Dahllöf, 2017). Both nickel and cobalt are scarce and expensive materials (Walther, 2012). Most of the world's cobalt comes from the People's Democratic Republic of Congo, a country known for its human rights violations (Walther, 2012).

Table 2 outlines more advantages and drawbacks of each technology. Both phosphate and cobalt are considered critical raw materials (European Commission, n.d.-a).

Table 2. Main battery chemistries and their advantages and drawbacks, adapted from Romare & Dahllöf (2017)

Technology	Use	Advantages	Drawbacks
LFP	Mostly used in China due to favorable regulation	Excellent power and safety, low degradation rate, cheap materials	Low energy density, use phosphate
NCA	Tesla	High energy density, voltage and power, less cobalt than NMC	High cost, use nickel and cobalt
NMC	All other manufacturers	Good performance, high energy density	High cost, use nickel and cobalt
LFP = lithium ion phosphate, NCA = nickel cobalt aluminum, NMC = nickel manganese cobalt			

Battery Lifetime

There is still no consensus concerning the EV and battery lifetimes. The LCA study assumptions range from 10 years and 150,000 km to over 560,000 km and 15 years (Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014). An assumed short lifespan has a significant non-beneficial effect on the environmental impact (due to for example battery replacement needs), and ongoing EV ownership costs. New studies show that batteries probably will last at least 14 years (Dahllöf, Romare, & Wu, 2019; Lam, Peeters, & Tichelen, 2019) and BEV batteries might even last well beyond 300,000 km (Electrek, 2019). If range degradation is not as severe as previously estimated, in some cases, the batteries might even outlast the cars.

Battery degradation is caused mainly by two factors, calendar aging or aging over time, and cycling aging, that is, the number of full charging and discharging cycles a battery goes through (Pelletier, Jabali, Laporte, & Veneroni, 2017; D. Wang, Coignard, Zeng, Zhang, & Saxena, 2016). Cycling aging has the most noticeable impact on battery degradation and can be interpreted as the number of kilometers driven. However, aspects such as driving style affect how far one can travel on one charge. To decrease the battery degradation, experts suggest avoiding full charging cycles when possible to preferably smaller charges throughout the day (Battery University, 2019). Additionally, longer, slower charges overnight are better than short, fast charging (Toll, 2018). Calendar aging should, however, not be neglected as a car can be parked around 95% of its lifetime (David Z, 2016; Saldaña et al., 2019). As calendar aging is highly dependent on temperature (Pelletier et al., 2017; D. Wang et al., 2016), keeping a parked car in a temperature between 10°C and 25°C will extend battery lifetime compared to more extreme temperatures.

A battery reduced to 80% of original energy capacity is generally considered to have reached its end-of-life (Casals, Rodríguez, Corchero, & Carrillo, 2019; Romare & Dahllöf, 2017). The main reason is that range performance is a function of battery capacity. An additional motive is a small reduction in power output and acceleration. As batteries become more extensive, the maximal range of a vehicle will become less critical. If a lower car acceleration is acceptable, a battery’s useful lifetime could be extended, meaning that the car could be of use until 50% battery capacity (Casals et al., 2019). If that is the case and the car will last as long as the battery, we will still see some of today’s EVs on the roads 30 years from now.

4 Infrastructure

Charging equipment and infrastructure are vital components to the successful adoption of EVs. The terminology and variations can however, be confusing. Important infrastructure players are energy companies and the electricity grid owners. To understand the views of these companies, interviews with some regional actors have been conducted.

4.1 Charging Equipment

Chargers are typically divided into four separate modes:

Mode 1 – This mode entails plugging the EV directly into a wall socket or an engine pre-heater outlet; an "emergency cable" is provided for most EVs. Although wall sockets tend to be 16 A, allowing charging speeds of 3.7 kW, outlets for engine warmers are usually limited to 6 or 10 A, restricting the output to 1.3 and 2.3 kW, respectively. Due to the risk of overheating during charging this type should be avoided whenever possible.
Mode 2 – Like in mode 1, the car is plugged into a regular socket but features a more specialized EV cable, generally providing either 10 or 16 A, and with a possibility to automatically turn off the power connection when the battery is fully charged. Although safer than mode 1, Elsäkerhetsverket (2019) still advises against all charging done without a dedicated wall box or charge point, as in Mode 3.
Mode 3 – In this mode, the charging is done through a dedicated wall box or charge point, which is safe and can include functionality such as power guards, limiting the power output when other household appliances run simultaneously.
Mode 4 – Fast or direct current (DC) charging offers the potential for considerably higher power outputs. Although the standard today is 50 or 120 kW, soon charging stations will go as high as 350 kW. In Sweden, there are three types of fast chargers available: combined charging system (CCS), Charge de Move (CHAdeMO), and Tesla proprietary connector (Nicholas & Hall, 2018). Not all cars are compatible with all charger types, and although public chargers are evenly split between the three, CCS is the European and Swedish preferred charging type and will likely develop faster than its competitors. Swedish law even requires public fast-charging sites to have at least some CCS compatibility (SFS 2016:917). Charging can also be categorized in levels. The levels, modes, power ranges, and connector types, relevant for the Swedish market, are summarized in Table 3.

Table 3. Overview of available chargers in Sweden, the installation cost for level 1 (higher limit) is from jula.se, and levels 2 – 3 from Emobility.se (2020). Excludes subsidies available through the "Ladda bilen" ("Charge the Car") scheme, see chapter 6.

Name	Level	Power (kW)	Mode	Connector Type	Installation costs (SEK)
Slow chargers	Level 1	≤ 3.7	Mode 1 – 2	Type C	0 – 5,000
	Level 2	> 3.7 ≤ 7.2	Mode 2 – 3	IEC 62196 Type 2 Commando Tesla connector	7,000 – 20,000
Semi-fast chargers	Level 2	> 7.2 ≤ 43.5	Mode 3	IEC 62196-2 Type 2 Tesla connector	20,000 – 50,000
Fast chargers	Level 3	> 36 ≤ 350	Mode 4	CCS Combo 2 CHAdeMO Tesla connector	200,000 – 500,000*

* For charging speeds up to 150 kW

Onboard and Fast Charging
Mode 1 – 3 uses alternating current (AC) with an onboard charger (also known as a rectifier) installed in the vehicle. The built-in charger transforms AC to DC, used by every modern battery. The alternative is using fast charging, which supplies DC directly to the car by converting from AC directly from within the charging station. Each car model defines the charging capacity, and even though all EVs have an onboard charger, not all cars have fast charging capabilities. The output of the charge box also limits the speed at which it is possible to charge an EV. It is the lower of the two that determines the maximum charging speed. Fast charging speeds are often denoted in time to reach 80% charge. The reason is that too much power close to the capacity limit increases battery degradation, and after 80%, the charging speed is therefore reduced (Nicholas & Hall, 2018).

4.2 Charging Infrastructure

Charging infrastructure is a critical component of EV adoption and infrastructure is typically divided into private and public charging.

Private Charging

Private chargers are considered not publicly available and are typically installed at home or at the workplace. It is estimated that around 75% of charging occurs at home, and approximately 20% at work (Hardman et al., 2018). For anyone wanting to install charging equipment, the price will depend on power output and the desired charging speeds, starting at around SEK 10,000/charge box plus installation costs. Slower charging speeds reduce expenses and are preferable for local grid companies as it also reduces network loads. For cars parked either all day or all night, higher charging speeds might not even be necessary[3]. There are no specific requirements when installing charging equipment. However, all interviewees mentioned a worry of local network overloads when the utility company is not consulted and encourages business owners to contact their grid company when installing new charging equipment. Companies are encouraged to utilize at least some smart steering capabilities, such as power guards, to reduce peak power needs and minimize grid congestion. Some of the utility companies also mention that the electricity tariff might be different in the future, charging more for power but also for energy during high load times, creating an incentive for consumers to manage their peak loads[4]. In other parts of the country, the electricity tariff has already moved somewhat in this direction (Ellevio, 2020; Karlstad Energi, 2020). Already today, there are likely cost savings to be made if SMEs can avoid changing their grid contract to a higher ampere connection[5].

Public Charging

Although public charging is currently estimated to make up less than 5% of all EV charging (Hardman et al., 2018), it plays a vital role in the adoption of EVs. Evidence suggests that despite the low usage, public charging can play an essential role in reducing range anxiety (Hardman et al., 2018; Nicholas & Hall, 2018), even if the drivers never use them (Anegawa, 2010). Tesla also utilized this fact when building out a vast charging network, creating range confidence for new EV users in the early stages of BEV adoption (Nicholas & Hall, 2018). Public charging can be divided into three categories: destination chargers, general parking chargers, and travel corridors.

Destination charging refers to charging stations in connection to shops, malls, and businesses that are publicly available. Investing in destination chargers might increase a companies' attractiveness and bring new customers by encouraging EV drivers to stop at your location[6]. "This is a radical shift in fueling behavior, charging where you go rather than going where you fuel."[7] Like private chargers there are no specific requirements for installing destination chargers and while people generally stay longer at a destination location than in a travel corridor, they do not stay as long as at home or work. Semi-fast chargers can, therefore, be an appropriate choice for installation. There is no standard financial payment model, and it is the prerogative of the owner of the charge box or parking space to set a tariff. It can either be per kWh or hour. At the concert hall of Gävle, for example, a parking spot with a charge box costsSEK 5 extra/hour. A standard is lacking on the technical side as well and drivers wanting the freedom to charge anywhere need to keep several charging cards[8].

Sandviken Energi and Gävle Energi have together installed more than 300 general parking chargers in the municipalities. Half the chargers have been installed for public consumption, and although currently free of charge, Sandviken Energi expects the cost to be around SEK 2.5/kWh incl. VAT once a payment solution is in place. The other half have been installed to serve the municipal car fleet, making them unavailable for public consumption. A hybrid solution is mentioned, keeping the parking spots private in the daytime and publicly available after working hours[9]. Such a solution

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[3] Hans Ädel (Gävle Energi).
[4] Hans Ädel, Teddy Hjelm, Anders Holmsten (Gävle Energi); Mikael Palm (Sandviken Energi); Jonas Sunryd (Ellevio).
[5] Michael Halvarsson (Ljusdal Energi).
[6] Mikael Palm (Sandviken Energi).
[7] Anders Holmsten (Gävle Energi).
[8] Michael Halvarsson (Ljusdal Energi); Anders Holmsten (Gävle Energi).
[9] Mikael Palm (Sandviken Energi); Anders Holmsten (Gävle Energi).

could be interesting for companies looking to provide EV charging for their employees while still earning some revenue in the evenings.

Travel corridors are networks of fast chargers installed along highways to enable long-distance travel, such as the one between Stockholm and Vemdal mountains (about 500 km). The corridor is initiated by Ljusdal Energi in collaboration with other municipal companies in the region. Although Ljusdal Energi's chargers are still free to use, Michael Halvarsson (Ljusdal Energi) foresees a pay-per-minute structure to encourage shorter stops. Fast charging can, in some places, be as expensive or even more expensive than fueling diesel, to recover the high installation costs (Edgren, 2020). Travel corridors could be susceptible to queues as they are often desired by many travelers at the same time (Daniel Asplund, Falu Energi and Vatten, personal communication, 2020); as an example, during the spring vacation weeks when many vacationers want to go skiing at the same time. A possible future scenario is enabling a booking arrangement to avoid overcrowding and low capacity. Due to the power requirement at fast-charging stations, the grid company needs to be contacted before any installations.

5 Distribution Grid

The technology for distribution of electricity and vehicle fuel has in essence not changed much over the last 100 years. The electrification of the transport sector is fundamentally changing the balance and could, in the long term, threaten the stability of the grid[10]. However, EV adoption is currently at such a slow pace that the local grid companies in Gävleborg do not consider additional effects due to EVs when operating and planning reinforcements in the grid[11]. Electrification is not contained to the transport sector but appears across all industries (e.g. working machines used in mining and agriculture) in an effort to reduce GHG emissions. On the other side, while traditional power production facilities are being decommissioned and are slowly replaced by wind turbines and solar power, increased total capacity is needed as well. This is due to a growing demand for electricity. Electricity infrastructure expansion is also costly and time-consuming, all adding challenges to the Swedish electric supply companies. “This is not only about electric vehicles’ power use alone. It is the rapid need of power capacity in the wake of increased digitalization and electrification that pose as a challenge, which have to be mitigated,” says Jonas Sunryd (Ellevio). There are three main issues related to the electrification of the transport sector: network overload, power quality, and frequency deviations (Shareef, Islam, & Mohamed, 2016). Smart charging can potentially diminish all three concerns (Habib, Kamran, & Rashid, 2015).

5.1 Uncontrolled and smart charging

Charging can be categorized as either uncontrolled charging or smart charging. If an EV is plugged in and charges with constant power regardless of grid conditions it is called uncontrolled or user-driven charging. Unrestrained charging can put tremendous stress on the distribution grid, and therefore smart charging is encouraged both by the grid companies[12] and the scientific community (Hedegaard, Ravn, Juul, & Meibom, 2012; Salah, Ilg, Flath, Basse, & Dinther, 2015). Schill and Gerbaulet (2015) go so far as to say “User-driven charging would raise severe concerns with respect to generation adequacy and may ultimately jeopardize the stability of the power system.”

Smart charging is a broad term for a system where a data connection is shared between the vehicle, the charging point and the charge point operator (Virta, 2020). Smart charging can be separated between user-managed charging and supplier-managed charging (Delmonte, Kinnear, Jenkins, & Skippon, 2020), where the former entails the use of variable tariffs to promote charging during low system consumption periods. Customers are then able to determine if they are willing to pay more to charge at any time or choose to optimize charging costs, promoting, for example, a shift of power use from the afternoon until later in the evening (Foley, Tyther, Calnan, & Ó Gallachóir, 2013). Examples of supplier-managed charging are forms of congestion management either locally or over larger areas, where multiple charging sites can be accessed simultaneously to vary loads to reduce grid stress. The supplier could either schedule different charging points over a time window to minimize network loads in advance and still meet customer needs (Foley et al., 2013) or respond to a stress event by turning down power output for all affected charging points simultaneously.

A more advanced form of smart charging is called vehicle-to-grid (V2G). With V2G a car can discharge the battery providing electricity to the grid. Using V2G can offer completely new services to the grid, while creating new revenue streams for the owner. The technology is, however, still immature with only a handful of models, such as the Nissan Leaf, that are V2G compatible. Almost no charging equipment installed today supports V2G. Coupled with higher costs, it will not offer financial value to invest in V2G currently.

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[10] Hans Ädel (Gävle Energi).
[11] Hans Ädel, Teddy Hjelm (Gävle Energi); Lennie Jonsson (Sandviken Energi); Michael Halvarsson (Ljusdal Energi).
[12] Hans Ädel, Teddy Hjelm (Gävle Energi); Mikael Palm (Sandviken Energi); Mikael Halvarsson (Ljusdal Energi).

5.2 Potential Grid Issues

As mentioned above, the main concerns to the electricity grid with regards to EVs are network overload, power quality concerns, and frequency deviations (Shareef et al., 2016). Network overload occurs when there is a higher load (in terms of kW) than what the system can supply. It can happen in large areas (city or region), but also in smaller zones such as in a local area or a house. It can be caused by either a lack of production capacity or if transformers and power cables are not dimensioned to handle multiple EV charging installations, which is the case in some areas of Sandviken and Ljusdal[13]. If a network overload is severe enough, it can cause a blackout in the affected area, which can in turn damage electrical equipment. Wang and Paranjape (2014) found that, while only investigating power (kW) and not energy (kWh), a 30% EV penetration in an area of 2,000 households would increase power demand by 53%.

Power quality issues such as voltage fluctuations and reactive power are mainly caused by high peak loads and large power fluctuations. For most people power quality is not an issue. However, sensitive electronic equipment can be damaged by large voltage fluctuations and, depending on the manufacturing, an entire production line can be destroyed if the power quality is not maintained at stable levels. Companies sensitive to power quality disturbances are encouraged to contact the grid company before installing new EV charging equipment. Furthermore, "voltage collapse can severely damage generation, transmission and distribution equipment, and result in widespread cascading blackouts" (Direct Business Energy, 2016). Despite the warnings that large-scale EV adoption can reduce power quality in the grid[14], Habib, Kamran, and Rashid (2015) suggest that the power quality can even be improved through successful use of V2G.

Maintaining a stable frequency is one of the fundamental aspects of a well-functioning grid. When there are discrepancies between supply and demand, the frequency fluctuates. As with network overloads and voltage fluctuations, if the frequency deviates too much, the grid will experience a blackout (Habib et al., 2015). V2G technology could, however, have a positive impact on frequency stability. While currently no incentive schemes or contracts are available to support such services, in the future EV owners can likely earn money by providing frequency support and even adopting wind and solar power[15]. This idea is supported by several studies, e.g. Hedegaard et al. (2012), Schill and Gerbaulet (2015).

[13] Lennie Jonsson (Sandviken Energi); Michael Halvarsson (Ljusdal Energi).
[14] Hans Ädel, Teddy Hjelm (Gävle Energi); Lennie Jonsson (Sandviken Energi); Michael Halvarsson (Ljusdal Energi); Jonas Sunryd (Ellevio).
[15] Jonas Sunryd (Ellevio).

6 Electromobility Policies and Costs

Sweden has set an ambitious target to reduce GHG emissions from the transport sector with 70% by 2030, compared to 2010 levels. In support of this goal, the Swedish government have enacted polices that could affect purchase decisions, in the first quarter of 2020, 27% of new car registrations was an EV (Bil Sweden, 2020). Another variable, dependent on policies, which ultimately affect purchases, is the total cost of ownership, summarizing all costs, not only the initial purchase.

6.1 Bonus-Malus

New Swedish cars registered after July 1st, 2018 are subject to the Swedish bonus-malus system, promoting sustainable transport. Cars registered before 2020 emitting less than 60 g CO_2/km and cars registered after 2020 and beyond emitting less than 70 g CO_2/km are eligible for a bonus while cars that emit more than 95 g CO_2/km are subject to malus tax (penalty) the first three years (Transportstyrelsen, 2020). The intention is that the tax should be cost-neutral, with malus tax paying for the bonus payouts. In 2019 alone, almost 1.3 billion SEK was paid out through bonus-malus (Transportstyrelsen, 2020).

In Norway, instead of a bonus-malus system, EVs are exempt from purchase tax and most of the registration tax. Although offering larger tax benefits than in Sweden, the tax system in Norway, similar to the Netherlands, promotes the purchase of a bigger car as the tax benefits increase the more you pay for your vehicle. In comparison, the Swedish bonus-malus system more effectively promotes more sustainable transportation, as cars of all costs and size segments are eligible for the same bonus, providing a relatively more significant bonus for smaller cars (Lévay, Drossinos, & Thiel, 2017).

Bonus

A premium of SEK 60,000 is applicable for cars with zero tailpipe emissions such as BEVs and FCEVs. For private individuals the bonus is reduced linearly by SEK 714 for each g CO_2/km up to 70 g CO_2/km (SEK 833 up to 60 g CO_2/km for cars before 2020). For example, a PHEV car emitting 40 g CO_2/km would get a premium of SEK 60,000 – 714 * 40 = SEK 31,440. For private owners the bonus can amount to a maximum of 25% of the total value of the car. In contrast, companies are eligible for at most 35% of the price difference between the EV and a comparative non-EV model, as decided by the Swedish Tax Agency (Skatteverket).

Malus

The malus system includes all gasoline or diesel cars emitting more than 95 g CO_2/km and results in an increased yearly road tax for the first three years. The malus tax consists of four components (depending on the fuel type) and is described in Table 4[16].

Table 4. Overview of malus cost scheme for Swedish bonus-malus system

Tax component	Fuel type	Yearly cost
Base tax	All fuel types	SEK 360
Environmental tax	Diesel	SEK 250
CO_2 tax	Gasoline, diesel	> 95 gram / CO_2 = 82 SEK /gram CO_2 > 140 gram / CO_2 = 107 SEK /gram CO_2
Fuel tax	Diesel	SEK 13.52 / gram CO_2

[16] For more information on the bonus-malus system, please visit: https://www.transportstyrelsen.se/sv/vagtrafik/Fordon/bonus-malus/

Company cars
In Sweden, a company car can mean one of two things. Either it is only used for work purposes, and privately less than 1,000 km per year, or it is used privately as well and is then considered an employee benefit. As such it is subject to tax. The taxable amount is decided by the Swedish Tax Agency and the driver pays marginal tax for the benefit. Similarly, the company pays the employer's general payroll tax on the same amount. It is therefore beneficial for both employees and companies to have a low benefit value. To promote the adoption of less CO_2 polluting cars, and account for the higher purchase costs of EVs, the Swedish government has reduced the taxable amount on EVs to the closest equivalent ICEV car. Also, in 2020 an additional yearly reduction of up to SEK 10,000 is in effect for EVs. An example of five common cars can be found in Table 5.

Table 5. Comparison of benefit values of selected cars on the Swedish market (Skatteverket, 2020)

Car	BMW i3 (BEV)	VW Golf (ICEV)	Kia e-Niro (BEV)	VW Passat GTE (PHEV)	VW Passat SC (ICEV)
Electric range (km)	296	-	455	56	-
CO_2 tailpipe (g/km)	0	125	0	37	148
Purchase price (SEK)	419,000	249,900	481,900	458,500	339,800
Benefit value (SEK)	217,900	249,900	226,300	292,700	339,800
Monthly benefit value (SEK/month)	2,042	3,486	2,107	2,649	4,206

For all car models any equipment besides a standard package (such as automatic transmission, snow tires, and air conditioning) increases the benefit value of the car and thereby increases the monthly benefit value. Additionally, the company that pays for the car usually includes maintenance and insurance. A typical payment structure for company cars is leasing, due to a 50% VAT reduction for company leased cars. Fuel for company travel and other operating expenses is tax-free (IF, 2020). Due to the different variables affecting the cost (such as yearly mileage, service package, number of cars in the fleet, pricing by different car dealers), it is difficult to provide a general cost estimate for company cars.

6.2 Urban Electromobility

Municipalities are already allowed to define environmental zones to restrict heavy traffic in certain areas. Starting January 1, 2020, two new environmental zones are available to ban gasoline and diesel cars, light trucks, and buses (Transportstyrelsen, n.d.).

- Environmental zone type 1 restricts heavy traffic, and exceptions are made based on emissions standards.
- Environmental zone type 2 restricts access for gasoline and diesel cars, light trucks, and light buses based on tailpipe emissions. The vehicle must adhere to Euro V or Euro VI standards, as specified by the European Union.
- Environmental zone type 3 applies to both light and heavy traffic and only allows electric vehicles, fuel cell electric vehicles, and gas cars that comply with Euro VI standards.

In Gävleborg the use of environmental zones does not currently seem to be of interest on the political agenda. Municipal transportation service and drivers with handicap parking permits are exempt from environmental zone regulation.

Klimatklivet and Ladda bilen
"The Climate leap" (Klimatklivet) is a national support scheme overseen by the Swedish Environmental Protection Agency (Naturvårdsverket) giving support to GHG decreasing measures. The program offers up to 50% subsidy to buy equipment for publicly available charging stations. Funds for private charging stations have been moved from this scheme to a scheme called "Charge the Car" (Ladda bilen), to enable citizens and companies to access the subsidy. "Charge the Car" can cover 50% of the total installation costs per charging point installed, and up to SEK 10,000 for individuals and SEK 15,000 for legal entities (i.e., companies, property owners, etc.) (Naturvårdsverket, 2020).

As of March 1, 2019, a total of SEK 449 million had been granted to 22,249 private (home and workplace) and 7,790 public charging stations (Naturvårdsverket, 2019a).

New Building Requirements for Charging Infrastructure
From the 15th of May, 2020, new requirements for charging infrastructure will come into effect (Prop 2019/20:81). The law, based on the updated European Energy Performance of Buildings Directive (2010/31/EU), states in more concrete terms that:

- New residential buildings, with at least ten parking spots, are required to set up electric wiring channels to each parking spot, simplifying charging installation when needed.
- New non-residential buildings, with at least ten parking spots, are required to set up electric wiring channels for at least a fifth of the parking spots as well as installing at least one charging box
- Existing non-residential buildings with at least 20 parking spots are required to install at least one charging box before 2025.

These rules would come into full effect for building permit applications submitted after March 10, 2021 and would apply only to heated buildings with the parking space located within the building or directly connected to it.

6.3 Total Cost of Ownership (TCO)

With purchase prices considerably higher for EVs than their ICEV counterparts, buying an EV can seem daunting. Besides being a new technology, the battery itself makes up around 25% of the total cost of the vehicle. Battery prices have, however, dropped around 17% per year in the last decade, suggesting that EV prices can be in line with ICEVs within the next few years (Nykvist et al., 2019).

A majority of businesses lease their cars (Philip Thunborg, Företagarna, personal communication, April 17th 2020), even though the TCO is of interest for SMEs to make it possible to compare the costs. The purchase price is not the only cost incurred by owning a car. It is suggested that consumers significantly underestimate the expenditures associated with operating expenses and thus overestimate the significance of the purchase price (Danielis, Giansoldati, & Rotaris, 2018; Hagman, Ritzén, Stier, & Susilo, 2016; Weldon, Morrissey, & O'Mahony, 2018). Using a total cost of ownership model, including all costs while owning the car, can help reduce this bias. Looking at overall costs becomes increasingly important when comparing an EV with an ICEV as EVs have a high initial cost and low operating cost. "That is what makes electric cars so fantastic; there are almost no costs after the initial purchase," says Mikael Palm from Sandviken Energi (personal communication, 2019).

National policies can have a significant impact on the overall costs (Hagman et al., 2016; Letmathe & Suares, 2017; Mitropoulos, Prevedouros, & Kopelias, 2017). In Sweden, the bonus-malus system is leveling the cost of ICEVs and EVs; an example is a comparison between the Volkswagen Golf (ICEV), one of the most popular cars in Sweden, and the BMW i3 (BEV). With a purchase price of around SEK 274,000 and SEK 419,000 respectively, for a holding period of three years, the monthly cost of ownership is about the same, a bit less than SEK 6,000 per month. A brief overview of the results from the total cost of ownership model can be found in Table 6. The TCO model is described in Appendix A and TCO results in Appendix B.

Table 6. Overview of the total cost of ownership (TCO), assuming 13,000 km per year

TCO (SEK)	BMW i3 (BEV)	VW Golf (ICEV)	Kia e-Niro (BEV)	VW Passat GTE (PHEV)	VW Passat SC (ICEV)
3 years (SEK)	204,630	215,730	243,340	277,640	239,360
6 years (SEK)	322,620	327,470	378,630	425,480	363,530
3 years (SEK / month)	5,680	5,990	6,760	7,700	6,650
6 years (SEK / month)	4,480	4,550	5,260	5,910	5,050

An interesting comparison is the ICEV Volkswagen (VW) Passat Sport Combi (SC) (SEK 290,000), one of the most popular company cars in Sweden, against its PHEV counterpart, the VW Passat

GTE (SEK 450,000) and the BEV Kia e-Niro (SEK 482,000). Kia e-Niro received the highest score in Gröna Bilister's competition "environmentally best car 2019" (Gröna Bilister, 2019). Despite having the highest purchase price of the three cars, Kia e-Niro is cheaper than VW Passat GTE and cost competitive with VW Passat SC. Besides the bonus subsidy of SEK 60,000 for Kia e-Niro, the VW Passat SC has GHG emissions of 148 g CO_2 per km, adding a total of SEK 15,000 extra in malus costs. With added SEK 10,000 per year in fuel costs (assuming 13,000 km per year) the VW Passat SC evidently has the highest operating costs of the three. The VW Passat GTE stands out, costing approximately 15% more than both VW Passat SC and Kia e-Niro, regardless of holding period.

The impact of driving distance becomes clear in a comparison between the Kia e-Niro and the VW Passat SC. For an annual driving distance of 7,800 km the Kia e-Niro costs SEK 6 per 10 km more and for an annual distance of 18,200 km, Kia e-Niro costs SEK 2 per 10 km less, than the VW Passat SC over 3 years, highlighted in Table 7. This points to another vital aspect of the total cost of ownership. The higher the mileage, the lower the average costs for an EV. Since electricity costs about 1.5 SEK per kWh, and gasoline and diesel around 15 SEK/liter, the connection between TCO and mileage is evident. However, there are always marginal scenarios. For example, if someone is driving long distances, they are more likely to use public charging stations (if driving EV) and would, therefore, have a higher cost per kWh.

Table 7. Overview of fuel costs and the total overall costs per 10 km (for three years) for VW Passat SC and Kia e-Niro, comparing the driving distances 7,800 km and 18,200 km per year.

	Driving distance (km / year)	**VW Passat SC**	**Kia e-Niro**
Total fuel costs (SEK)	7,800	22,680	5,370
	18,200	52,920	12,530
Total overall cost (SEK / 10 km)	7,800	96	102
	18,200	47	45

The holding period also plays a central role in the TCO model. This period does not change the cost ranking of the cars significantly. Owning any car for six years rather than three, reduces the monthly cost of ownership by almost 25% as seen in Table 6. The purchase price plays an essential role as it is a significant one-time expense, while holding the car for an extended period will spread out the high initial cost over more months. The depreciation also needs consideration, which is known to decrease more slowly as the car gets older. That means that the value of the car will reduce less in year four to six than it does in year one to three. For the BMW i3, a holding period of six years rather than three, reduce the monthly cost by SEK 1,200 per month, and for the VW Passat GTE the reduction is SEK 1,790 per month. In this report a depreciation model determined by Raustad (2017) is used. Raustad (2017), compiled the model using empirical data from several EVs and therefore the same depreciation is used for all cars in this report. The depreciation can however, vary quite a bit from car to car and assuming the same depreciation for each model might therefore be misleading. Combining the findings of Hagman et al. (2016) and Raustad (2017) suggests that EVs depreciate as much as 24% less than ICEVs. With new data also suggesting that batteries might last 14 years instead of previously assumed 8 – 10 years (Lam et al., 2019), the business case for EVs is likely to improve further.

It should be noted that the review for this report only considers the ownership costs, thereby excluding societal costs of, for example pollution and GHG emissions. Letmathe & Suares (2017) found that when including the societal costs, some EVs are cheaper (for the society) even without subsidies over a holding period of five years.

7 Environmental Arguments

Road transport contributes to approximately one-quarter of all EU greenhouse gas emissions and is the leading cause of air pollution in cities (European Commission, 2019). Transportation is the only major sector in the EU where greenhouse gas emissions, including carbon dioxide emissions, have not declined (European Commission, 2019). Even though there has been a decrease in greenhouse gases per vehicle in countries such as Sweden, this does not compensate for the increased number of vehicles on the roads (Naturvårdsverket, 2019b; Trafikverket, 2020). The EU strategies focus on reducing the emissions of road transport via measures such as prioritizing low- and zero-emission vehicles (European Commission, 2019). However, road transport does not cause climate change only during use. There are also significant land use and human health impacts during phases such as material extraction and manufacturing (Binnemans et al., 2013; K. Cullbrand & Magnusson, 2011; Hawkins, Singh, Majeau-Bettez, & Strømman, 2013; Notter et al., 2010; Smith Stegen, 2015; Steen, Kushnir, Ljunggren Söderman, Nordelöf, & Sandén, 2013).

System-level measures are needed to decrease vehicle dependence and to encourage walking, cycling, public transportation, online meetings, and the coordination of cargo transport (Naturvårdsverket, 2019b; Trafikverket, 2020). Additionally, existing road transport must be further improved on the product and component levels. These actions could involve the introduction of more electric vehicles, biofuel high-efficiency internal combustion engines (ICE), new materials for light weighting and other low emission measures.

All products, such as EVs, have environmental impacts throughout their life cycle. Life cycle assessment (LCA) is a method for assessing the potential environmental impacts of a product, system, or service throughout its life cycle (ISO, 2006). The life cycle of a product begins with the extraction of raw materials, followed by manufacturing, the use phase, and the concluding end-of-life phase (i.e., waste management). During this life cycle, the product requires inputs in the form of resources and energy but also emits outputs such as emissions to air, soil, and water. Based on these inputs and outputs, a set of indicator scores are calculated and presented as different environmental impact category indicators such as global warming potential (GWP), resource depletion, human toxicity, and freshwater eutrophication.

7.1 Electric Vehicles from a Life Cycle Perspective

From a life cycle perspective, most studies conclude that EVs have the potential to reduce carbon dioxide emissions during the use phase compared to ICEVs. Different complete life cycle emission reduction rates favoring EVs are reported in the literature varying from 10% to 24% (Hawkins et al., 2013) to almost 50% (Ma, Balthasar, Tait, Riera-Palou, & Harrison, 2012). These savings occur mainly as a result of fuel change (from fossil fuels to less carbon-intense electricity), reduced tailpipe emissions and improved engine efficiency (Hawkins et al., 2013; Ma et al., 2012). But the savings also depend on underlying assumptions concerning electricity mix, driving range and more (Faria et al., 2013; Hawkins et al., 2013; Ma et al., 2012; Messagie, Boureima, Coosemans, Macharis, & Mierlo, 2014). The connection to the use phase assumptions is further explained below.

7.1.1 Raw Material Extraction and Manufacturing Life Cycle Phases

Raw material extraction is the first life cycle phase and could include mining for virgin ores, extraction of oil, and other resources, or preparing recycled materials for manufacturing. Most virgin raw material extraction have a high energy demand, water and land use. Environmental impacts are also caused by emissions to air, water, and soil. There also are significant environmental impacts during the processing of ore to usable material due to energy requirements, use of chemicals, process waste, and spillage. The potential reduction of use phase environmental impacts with the introduction of EVs depends on advanced technology based on materials such as rare earth elements (REE), lithium, or cobalt (K. Cullbrand & Magnusson, 2011; Steen et al., 2013). These materials could potentially offset the EV impact savings in the use phase. REE such as neodymium, dysprosium and others can be found in the magnets and traction batteries of most EVs. It is worth noting that modern ICEVs also need these raw materials for electrical and electronic equipment in the car.

During manufacturing the materials are processed, molded, and assembled into a product. During this life phase, environmental impacts occur due to energy use, resource use, and production waste.

Impacts of manufacturing are generally considered one of the lowest impacts for conventional vehicles. But with the development of EVs this is shifting and manufacturing is no longer insignificant (Hawkins et al., 2013). Batteries and other advanced electronic components are responsible for this environmental impact shift due to their materials and intensive production processes (Hawkins et al., 2013; Ma et al., 2012). Since the manufacturing phase increases its effect on the life cycle impacts, aspects such as electricity mix have an decisive influence on the magnitude of the environmental impact (Majeau-Bettez, Hawkins, & StrØmman, 2011). As the environmental impact of the use phase decreases, the raw material extraction and production stages of the EV become more critical from a life cycle perspective (Hawkins et al., 2013; Ma et al., 2012).

A life cycle perspective is essential to detect impact shifts and make a meaningful comparison between EVs and ICEVs (Figure 1). In the case of EVs, impact shifts such as from energy use and climate change to resource depletion, human toxicity, etc. are observed (Hawkins et al., 2013; Notter et al., 2010). If meaningful impact categories are not assessed, the increased environmental impacts of raw materials may be overlooked. This mistake, in turn, may entail a risk of overestimating the potential benefits of EV technology.

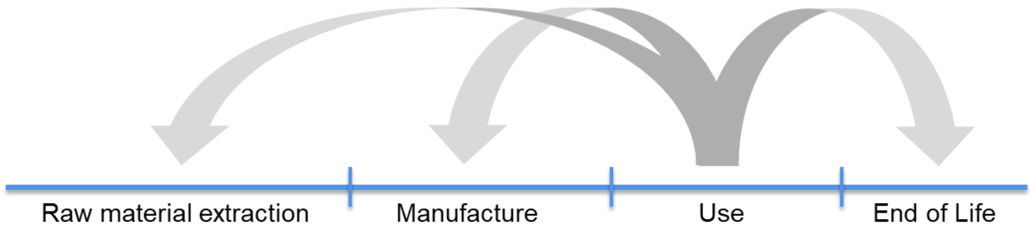

Figure 1 Compared to an ICEV, the impacts during the use phase will decrease, but there is a risk that environmental impact shifts to other life cycle phases.

7.1.2 Consideration and Assumptions in the Use Phase

With an energy efficiency of up to 95% and zero tailpipe emissions, BEVs are currently the most prominent alternative to reduce emissions during the use phase, enough to reach regional and national targets. Assumptions connected to, for example, PHEV mode (charge-depleting or charge-sustaining mode), electricity mix, driving range, car and battery lifetime affect the environmental impact and the LCA result. In the case of the PHEV, the division between renewable electricity and fossil fuel driving will of course influence the environmental impact. The electricity mix used to charge a BEV or PHEV has a significant effect on the potential environmental impact of the vehicle. An energy mix primarily consisting of fossil fuel combustion has limited benefits (Hawkins et al., 2013; Ma et al., 2012). The Swedish electricity mix, mainly consisting of hydro and nuclear power, is less carbon-intense leading to a lower impact on for example climate change compared to fossil incineration.

Environmental performance of cars is usually presented in relation to one km driven (1 vehicle-km). In comparing different vehicle technologies, the lifetime both in terms of ageing (for components such as the battery) and the number of km driven are essential factors. As a comparison, the TCO decreases with the mileage and holding years, since the cost is distributed onto more kms and years. Simply put, the environmental impact of the raw materials and manufacturing can similarly be spread out on the use phase.

Range and environmental impact are affected by driving patterns. A recent study has found that aggressive driving can use 50% more energy and degrade the battery up to almost 40% more compared to careful driving (Jafari, Gauchia, Zhao, Zhang, & Gauchia, 2018). As more energy is needed, the battery needs to be charged more often, hence degrading faster. Reduced driving speed and acceleration will increase the range, the lifetime of the car, and reduce the electricity needs. Current research shows that the EV batteries can potentially outlive the vehicle, prolonging the use phase to at least 14 years (Dahllöf et al., 2019; Lam et al., 2019). A longer life span is significantly beneficial from an environmental perspective; the material and production impacts per km will decrease.

7.1.3 *Vehicle and Battery End-of-Life*

Waste management of end-of-life vehicles (ELV) in EU are regulated by the ELV directive (The European Parliament & The Council of the EU, 2005), aiming primarily to prevent waste and additionally to promote reuse, recycling, and recovery of vehicle material. Required reuse and recovery rate is 95% of the total vehicle mass, of which at most 10% can constitute energy recovery. All road vehicles with a weight less than 3.5 tons are regulated under the ELV directive, including EVs. The most widely used management of ELVs is shredding; afterwards, the pieces are separated into basically magnetic, heavy and light material fractions. There is, unfortunately, a lack of reliable statistics on at what rate ELVs are material recycled (Andersson, Ljunggren Söderman, & Sandén, 2017; Binnemans et al., 2013; F. K. Cullbrand, Fråne, & Jensen, 2015). It is clear, however, that higher recovery is important for the environmental benefit of EVs.

The increased material mix in EVs, including ICEVs in some cases, means that waste management should be adapted to be able to recover material resources. One suggestion is focusing on the value of the material and not just the mass fraction since many critical raw materials are used in small amounts (for example, rare earth materials) (Gradin, Luttropp, & Björklund, 2013). Although many studies highlight the importance of responsible use and recovery of these elements (Binnemans et al., 2013; Smith Stegen, 2015), recycling rates for REE remain negligible (Andersson et al., 2017; Binnemans et al., 2013).

Strong uptake of EVs will result in the availability of terawatt-hours of batteries that no longer meet the required specifications for usage in an EV (Engel, Hertzke, & Siccardo, 2019). After remanufacturing, such batteries are still able to perform sufficiently to serve less demanding applications, such as stationary energy-storage services (Engel et al., 2019). The second life of batteries can reduce the negative effects of energy-intensive production. In other applications such as grid support, the useful life of batteries can be extended. From a waste hierarchy perspective, this is a more favorable option than the recycling of materials or energy recovery (The Council of the European Union, 1999).

Highlights

- Life cycle assessment (LCA) is used to evaluate the potential environmental impact of, for example, EV throughout its life cycle from material extraction to waste management.
- There is a need to not only decrease the environmental impact per vehicle but also to decrease the number of vehicles, to reach a more sustainable transport system.
- The EV has the potential to significantly decrease impacts during the use phase, especially concerning exhaust emissions.
- The environmental impacts difference between EVs and ICEVs are connected to:
    a. use of energy-intense materials in batteries and electric motors
    b. the rate of renewable energy in the electricity mix used during charging
    c. material recovery at the vehicle end of life
- A longer lifetime of the battery and a higher use time mileage add benefits for the EV from an environmental perspective.

8 Discussion and Conclusions

The overall intention of this report has been to understand “the current state of EV technology and EV infrastructure” with regards to potential EV adoption in Gävleborg, in particular for SME’s. To support the answer of the primary research question, three additional questions were posed and investigated.
The second question concerning regional utility companies is initially discussed in this chapter. Then the third question about the total cost of ownership, including range performance is answered. The fourth and final question regarding life cycle aspects is discussed. At the end of this chapter, the conclusions and possible future work are presented. Study limitations and potential effects on the results are also discussed in each of the first three sections.

8.1 Regional Utility Companies

Question two: What are the regional utilities' views on EV adoption in relation to grid infrastructure?

A potential risk is the strain a large fleet of EVs can put on the electricity grid. For that reason, grid companies in Gävleborg were interviewed for their opinions. A shared sentiment is that there is a small concern about EV significantly impacting local grids in the short term. As the EV fleet increases, smart charging will play an essential role in mitigating problems, such as reduced power quality and grid congestion. A shared view is that electricity tariffs will likely change in the future. As peak loads become a bigger problem, power in general and energy consumed during peak periods will become more expensive. The new tariff structures might warrant companies taking a more active role in their energy consumption to reduce costs. All interviewees would also like to see a better overview of private, and public, charging installations as it affects grid planning. A suggestion would be to legislate an enforced notification of new installations to the grid company. Such regulation could improve grid companies’ ability to support weaker areas of the grid faster.

The interviews represent the subjective views of the interviewees and might, therefore, not provide a complete picture. A potential limitation was that not all grid companies in Gävleborg were contacted, and there might be variations in local views. The perception of some of the interviewees, based on cooperation and discussions among the grid companies, is that local grid companies share a similar sentiment regarding EVs in the region[17]. The literature review, however, substantiated the responses and at least did not contradict the opinions shared by the interviewees.

A motivating aspect of EV battery technology is the positive impact it can have on the build-out of renewable energy sources such as wind and solar. Due to the intermittency of wind and solar, it can be challenging to match supply and demand. As a consequence, the need to be able to store energy becomes coupled with the expansion of intermittent power sources. The batteries in EVs are storage units and if EVs can be purposed to charge during periods of excess wind and solar, less stationary battery capacity will be required. Furthermore, as there is still useful capacity in the batteries even after having reached the vehicle end-of-life (at a 20% capacity loss), they can be re-used as stationary storage supporting renewable power integration even more.

8.2 Cost of Ownership and Range

Question three: What policies promote EV adoption, and how do they affect the cost of ownership?

One of the main arguments for choosing ICEVs over EVs is the high purchase price of an EV. Battery prices have dropped over the past decade. As the battery makes up a significant fraction of the cost, car prices have also gone down significantly. Additionally, the Swedish bonus-malus system further reduces the price gap between ICEVs and EVs (and other more sustainable transportation fuels). Coupled with significantly lower operating costs such as fuel and maintenance, some EVs are already cost-competitive.

[17] Lennie Jonsson (Sandviken Energi); Mikael Halvarsson (Ljusdal Energi).

Battery lifetime uncertainty and second-hand market interest have also caused concerns regarding the long-term value of EVs. However, there is evidence to support a slower value depreciation for EVs than ICEVs. New studies suggest batteries will last at least 14 years, almost 50% longer than previously anticipated; this will likely increase the second-hand car value further. The residual battery value should also increase with improved recycling and especially re-use practices, such as battery second life for grid support. Longer battery lifetime and enhanced end-of-life practices will not only increase the financial value, but they will also improve the environmental performance of EVs.

The TCO done in this report is not exhaustive and has been done with assumptions regarding driving distance, driving style, fuel costs, resale value, discount rate and interest. Interest assumptions are based on Hagman et al. (2016). Out of these, the resale value will likely be the most uncertain. It has been assumed that EVs and ICEVs depreciate at the same rate, although some researchers suggest that EVs maintain their value better than ICEVs (Hagman et al., 2016; Raustad, 2017). Regardless, the numbers stated should not be seen as definitive proof that EVs are cheaper than ICEV, but rather an indication that they have now become cost-competitive in Sweden.

A common argument against EVs is the limited range. While earlier models certainly had a range disadvantage, today two-thirds of models on the Swedish market boast a range above 300 km. With a Gävleborg average daily car travel distance of 32 km and 98% of trips shorter than 300 km (Liu et al., 2015), the range of new EVs should certainly be enough for most people. An overwhelming majority of charging occurs either at home or at the workplace, suggesting that long charging times might be more of a psychological barrier than a technical one. The Swedish government has contributed about SEK 500 million to build out the charging infrastructure, for private and public charging stations. Although a small portion of the market, public charging infrastructure plays an essential role in the development of EVs. With destination charging locations with 50 kW and travel corridors in some places now offering charging speeds of 30 minutes or less, concerns of long charging times should be reduced. If a more extended range is preferable, PHEVs are an alternative with better fuel economy than ICEVs. For daily commuters able to drive all or most of the range on electricity, PHEV can significantly reduce costs and GHG emissions while driving.

8.3 Environment

Question four: What life cycle aspects are decisive for the environmental impact of EVs?

With the imminent threat of climate change, our fossil fuel dependence needs to be reduced rapidly. In both Sweden as a whole and in Gävleborg, transportation is responsible for a large portion of overall GHG emissions. Changing travel patterns, and moving towards more sustainable fuels such as biodiesel, biogas, and electricity are critical to be able to reduce the impact. The transport sector generates 42% of Gävleborg's GHG emissions, and the use of EVs and other more sustainably fueled vehicles can significantly decrease the amount of GHG emissions released into the atmosphere. Local air quality in cities can also improve if EVs replace conventional cars, particularly zero tailpipe emission vehicles such as BEVs and FCEVs.

It is difficult to pinpoint the exact reduction in environmental impact caused by a shift from conventional vehicles to EVs. Several aspects affect the outcome, such as the lifetime of batteries, driving style, the raw material extraction process, and share of renewable energy during charging and manufacturing of components. An aspect that illustrates the complexity of environmental impact are so-called rebound effects. The rebound effect is an undesirable effect of an impact reduction measure. For example, if a user obtains an EV, this could lead to the user buying yet another fossil fuel vehicle to counter the range anxiety. This behavior would, of course, be less environmentally beneficial. One more rebound effect example is that the EV user can indulge in more travel (in frequency and distance) since the EV has lowered "the user environmental impact" (Langbroek, Franklin, & Susilo, 2017).

The energy-intensive production of EV batteries has caused debate concerning GHG emissions alongside the emissions caused by electricity generation for charging. The discussion highlights the need for renewable energy throughout the entire life cycle, additionally indicating the close connection between energy generation and the transportation sector. Sweden, with 80% of electricity coming from nuclear and hydro power, has the potential to significantly reduce GHG emissions with a widespread EV adoption. The need for renewable energy is relevant for both use phase charging and component manufacturing, for example, the potential significance of Northvolt's intention to produce EV batteries in Sweden (Northvolt, 2020). Despite uncertainties, the science community is largely in agreement that, under most conditions, EVs have a lower overall impact on GHG emissions than ICEVs.

Batteries and the electric motor require REE and other materials, such as nickel and cobalt. Mining operations are known to harm the environment, particularly locally, for example, through increased ground toxicity. Some materials are also extracted in conflict zones, calling into question the working conditions of the miners. One such example is Congo, the world's largest exporter of cobalt, where UNICEF estimates that some 40,000 children are working in the mines (Walther, 2012). Mineral prospecting and mining could possibly be expanded in Sweden, and the country has some of the most stringent environmental and social security laws. There is, however, local resistance against such efforts (Uppdrag Granskning, 2019). If we are to maintain our current level of comfort the demand for raw materials to provide new technology will increase. If we are not prepared to support more sustainable mining locally are we then willing to ignore the consequences of poor mining elsewhere, to support our continued way of life?

Arguably the current issues with mining extraction are severe but should not be a principal reason to buy an ICEV instead of an EV, but it is central to consider that striving to reduce GHG emissions might cause other environmental or societal consequences. This is the potential impact shift described in chapter 7. There are ways for users to directly reduce the environmental impacts of EVs. In summary these are to promote a longer lifetime and mileage, and use renewable electricity for charging.

8.4 Conclusions and Future Work

Question one: What is the current state of EV technology and EV charging infrastructure?

In summary, the current state of technology and infrastructure is promising. This report set out to understand if EVs are a viable option for SMEs in Gävleborg. One reason for the slow adoption rate of EVs could be that reduced GHG emissions and improved air quality are seen as societal benefits and not for users themselves (Sandén, 2017). However, reviewing the main concerns of cost, range, and charging times, the conclusion is that EVs have now reached a stage where they should provide a real alternative to ICEVs. Despite the difficulty of definite conclusions, there is enough evidence to show that EVs emit considerably less GHG emissions during their lifetime than ICEVs, particularly in Sweden. SMEs looking to reduce their climate impact can now choose EVs without having to compromise with price and comfort.

EVs, and particularly BEVs, have been the focus of this report. Despite the similarities, FCEVs have a different value chain and infrastructure, since the car is fueled by hydrogen. FCEV technology is still in its early stages but could offer advantages compared to other EVs, and looking more into FCEVs is, therefore, a good alternative for future research. Heavy transportation has also not been reviewed in this report. Some evidence suggests that large haul trucks could favor FCEV technology over BEV, since significantly smaller batteries are required, reducing charging times and overall weight of the transport, warranting further investigation.

Furthermore, a holistic view is required to understand how Sweden in practice can truly reach carbon neutrality. A systems perspective, taking into account driving patterns and behaviors, as well as the relation between electricity, hydrogen, and renewable fuels, such as biogas and biodiesel, will help regional actors find their opportunities to reduce environmental impact.

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Appendix A

Total cost of ownership (TCO) is calculated with the following formula:

TCO = Purchase price – Subsidy – Resell Price + ∑ (Total km driven * Fuel price * Fuel consumption + Insurance + Maintenance + Tax + Interest) * (1 + discount rate)^n

Purchase price is taken from manufacturer's website, basic model

Subsidy is defined by the Swedish bonus malus system

Resell price is calculated by (Purchase price – depreciation)* (1 + discount rate)^n .
Depreciation is calculated using, derived from empirical data of electric vehicle depreciation (Raustad, 2017):
$y = 6*10^{(-5)} * n^3 – 0.0038n^2 + 0.093n + 0.1384$
Where "n" is the year in which the car is resold

Total km driven is the yearly driving distance

Fuel price:
Gasoline SEK 15.50/l
Electricity SEK 1.5/kWh

Fuel consumption is taken from manufacturer's website. Exception is VW Passat GTE, collected from bilsvar.se "Bränsleförbrukning omräknat i bensin" to approximate the cost of both petrol and electricity.

Insurance and **maintenance** are taken from bilsvar.se website

Tax is calculated using the Swedish Tax Agency (Skatteverket) tax model

Interest is the financial cost of taking a car loan. Assumptions regarding interest rate (4%), down payment (20%) and payback time (three years) have been taken from Hagman et al. (2016). The bonus (if available), is assumed to amortize the loan, reducing the overall interest costs. For simplicity, the model assumes the money to be available from day one, although the bonus will not be paid until after six months of ownership.

Where (1 + discount rate)^n is the net present value formula, annualizing future cash flows and "n" is the year in which the cost is incurred. The discount rate is the opportunity cost of money, set to 4%

Appendix B

Data referenced in the report is highlighted in the table.

	Car Model	VW Passat GTE	VW Passat SC	BMW i3	Kia e-Niro Advance	VW Golf
Input variables	Fuel type	Petrol/Electricity	Petrol	Electricity	Electricity	Petrol
	Emissions (g CO2/km)	31	148	-	-	124
	Fuel consumption (fuel type/10 km)	0.324	0.650	1.520	1.590	0.550
	Purchase Price (SEK)	464,900	289,900	419,200	481,900	273,900
	Down Payment (SEK)	92,980	57,980	83,840	96,380	54,780
	Charge Box Purchase (SEK)	10,000	-	10,000	10,000	-
	Bonus Malus - Bonus (SEK)	37,866	-	60,000	60,000	-
	Insurance (SEK/year)	4,000	4,000	4,000	4,000	4,000
	Maintenance (SEK/year)	9,000	6,500	4,500	6,000	5,500
Fixed variables (three years)	Resell Value (SEK)	254,250	158,540	229,260	263,550	149,790
	Capital Expenses (SEK) Purchase price - Bonus Malus - Resell price	182,780	131,360	139,940	168,350	124,110
	Taxes (SEK)	1,040	14,160	1,040	1,040	7,900
	Insurance & Maintance (SEK)	37,520	30,300	24,530	28,860	27,420
	Interest Payment (SEK)	37,080	25,740	30,570	36,130	24,320
7,800 km (three years)	Fuel Costs (SEK)	11,310	22,680	5,130	5,370	19,190
	Total Cost (SEK)	**269,730**	**224,240**	**201,210**	**239,750**	**202,940**
	Cost per month (SEK/month)	7,493	6,229	5,589	6,660	5,637
	Cost per 10 km (SEK/10 km)	115	96	86	102	87
13,000 km (three years)	Fuel Costs (SEK)	18,840	37,800	8,550	8,950	31,990
	Total Cost (SEK)	**277,260**	**239,360**	**204,630**	**243,330**	**215,740**
	Cost per month (SEK/month)	7,702	6,649	5,684	6,759	5,993
	Cost per 10 km (SEK/10 km)	71	61	52	62	55
18,200 km (three years)	Fuel Costs (SEK)	26,380	52,920	11,980	12,530	44,780
	Total Cost (SEK)	**284,800**	**254,480**	**208,060**	**246,910**	**228,530**
	Cost per month (SEK/month)	7,911	7,069	5,779	6,859	6,348
	Cost per 10 km (SEK/10 km)	52	47	38	45	42
Fixed variables (six years)	Resell Value (SEK)	157,050	97,930	141,610	162,790	92,530
	Capital Expenses (SEK) Purchase price - Bonus Malus - Resell price	279,980	191,970	227,590	269,110	181,370
	Taxes (SEK)	1,960	17,170	1,960	1,960	9,560
	Insurance & Maintance (SEK)	70,870	57,240	46,340	54,520	51,790
	Interest Payment (SEK)	37,080	25,740	30,570	36,130	24,320
7,800 km (six years)	Fuel Costs (SEK)	21,360	42,840	9,700	10,140	36,250
	Total Cost (SEK)	411,250	334,960	316,160	371,860	303,290
	Cost per month (SEK/month)	5,712	4,652	4,391	5,165	4,212
	Cost per 10 km (SEK/10 km)	176	143	135	159	130
13,000 km (six years)	Fuel Costs (SEK)	35,590	71,410	16,160	16,900	60,420
	Total Cost (SEK)	**425,480**	**363,530**	**322,620**	**378,620**	**327,460**
	Cost per month (SEK/month)	5,909	5,049	4,481	5,259	4,548
	Cost per 10 km (SEK/10 km)	182	155	138	162	140
18,200 km (six years)	Fuel Costs (SEK)	49,830	99,970	22,620	23,660	84,590
	Total Cost (SEK)	**439,720**	**392,090**	**329,080**	**385,380**	**351,630**
	Cost per month (SEK/month)	6,107	5,446	4,571	5,353	4,884
	Cost per 10 km (SEK/10 km)	188	168	141	165	150

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