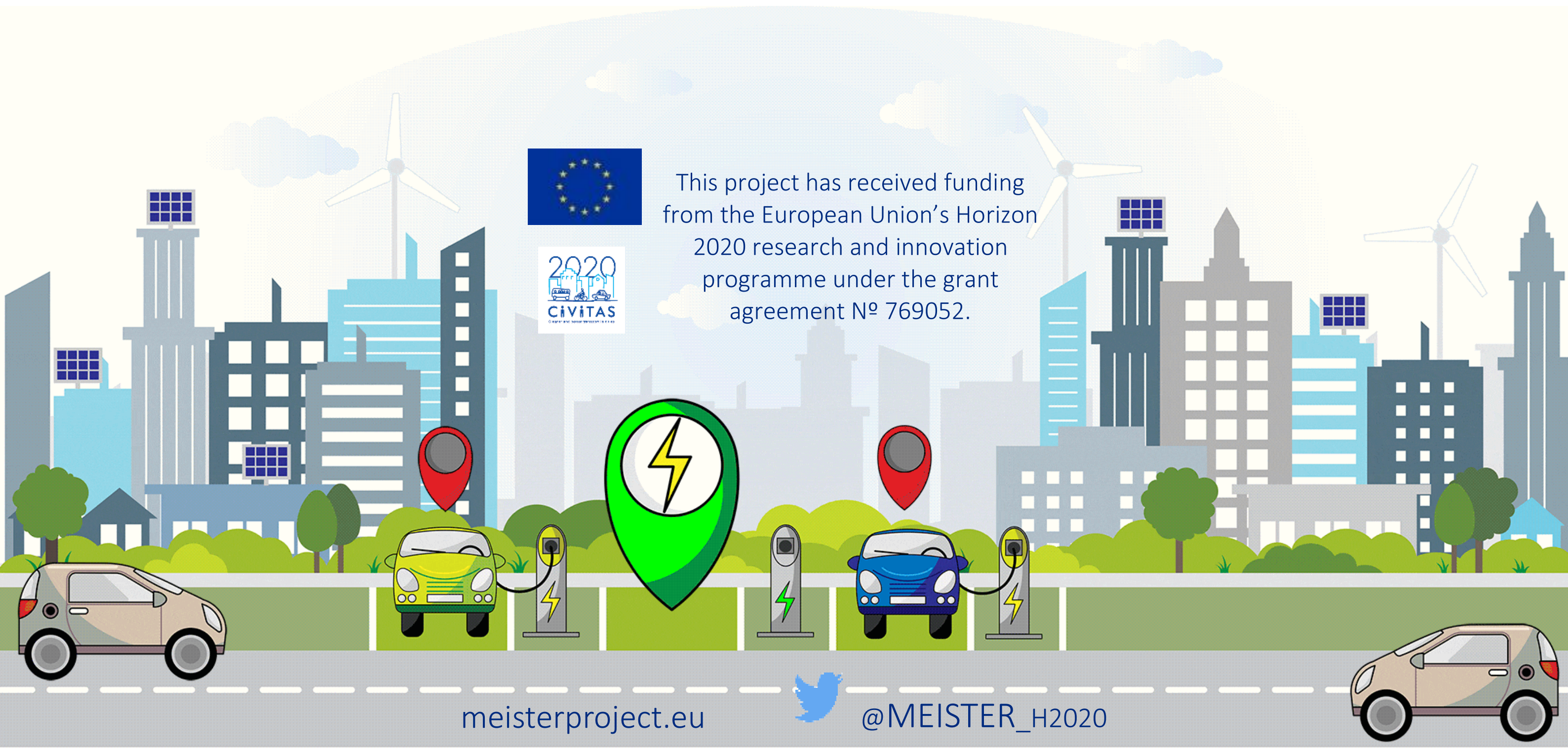
Recommendations for Charging Infrastructure in Stockholm County

Targeting Full Electrification of Passenger Cars by 2030

11 November 2021

Jakob Rogstadius

RISE Research Institutes of Sweden



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REPORT

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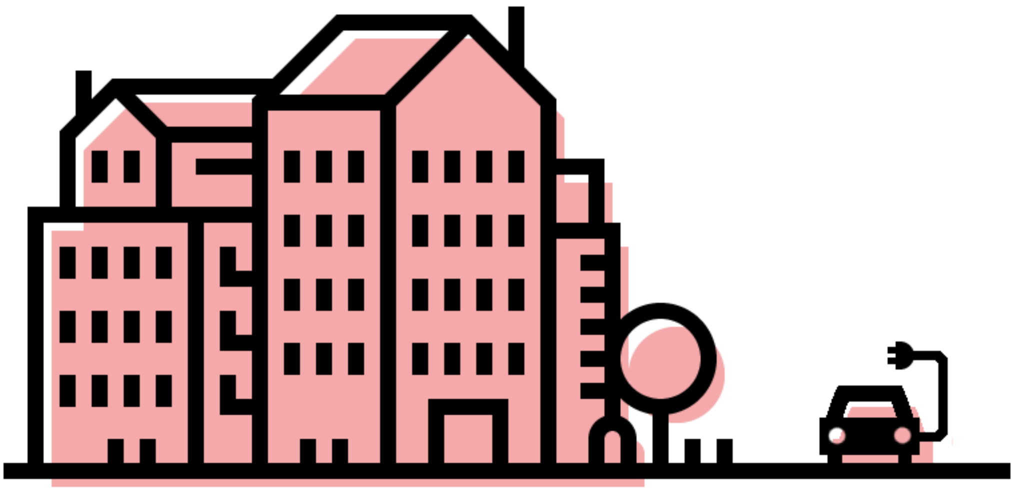

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Executive Summary

The City of Stockholm aims to enable electrification of road vehicles to reduce emissions of greenhouse gases, particles and noise from city traffic. Operation of electric vehicles requires substantial investments in charging infrastructure and much is still unclear regarding where to best install it, who should invest and operate it, and how much infrastructure is needed to enable electrification of the vehicle fleet.

Research Questions

This report breaks down and compares internalized and externalized costs associated with operation of battery-electric and internal combustion engine vehicles, to estimate the total socio-economic value of electrification of passenger cars. We compare incentives for private and public actors to invest in charging infrastructure for passenger cars and relate these to forecast demand for charging.

By applying a network model capable of handling interaction effects to the geographic region of Stockholm County, we identify sets of static charging infrastructure that minimize cost, ensure equal access to charging and are sufficient to deliver the necessary energy to a future fully electrified car fleet. The placement model is integrated with cost models for static charging infrastructure, grid related costs and indirect costs. For the proposed placement and density of charging infrastructure, we calculate and compare the resulting cost (but not price) of passenger car charging. We also calculate whether dynamic charging with electric road systems would provide cost savings in relation to static charging solutions.

A spreadsheet containing all parameter assumptions, calculations, tables and figures is included with the report as supplementary material, to enable what-if-analysis, adaptations to future real-world development, and replication of the study in other cities.

Results

Approximately 90% of the traffic work from passenger cars in Stockholm County is forecast to be electric by the year 2030, unless slow expansion of charging infrastructure breaks the current trend for newly registered vehicles. (*Figure 8*)

Current substantial subsidies of fossil fuel use in the form of undertaxation of fossil greenhouse gas (GHG) emissions result in that the public sector has a much stronger economic incentive than private actors to invest in charging infrastructure for electric cars over at least the coming decade. If greenhouse gas emissions are not taxed in proportion to the socioeconomic cost they incur, corresponding subsidies for electric vehicles and / or charging infrastructure would be needed for private and public actors to have equal incentives to invest in the conversion. Increasing the ratio of biofuels in diesel and petrol contributes to such internalization, without raising system-level costs for combustion engine cars. Full internalization requires increased taxation of fossil CO_2 emissions, unless biofuels become carbon neutral. (*Figure 4, Figure 18*)

Passenger car electrification within Stockholm County (pop. 2.5 million, 1 million cars) can generate *annual* socio-economic cost savings worth approximately 18 (11)[1] billion SEK by

[1] Numbers in parentheses are excluding the value of reduced untaxed fossil greenhouse gas emissions from fuel combustion. The analysis assumes a gradually increasing ratio of biofuel use in combustion engine cars and slowly increased taxation of GHG emissions, which together contribute to a gradual internalization of emission-related costs. BSEK means billion Swedish kronor, 10 SEK are approximately worth €1.

2030 and 22 (18) billion SEK by 2040. The *cumulative* cost savings are approximately 100 (50) BSEK by 2030 and 300 (200) BSEK by 2040. Each year that the transition is delayed or accelerated is associated with an opportunity cost of approximately 16 (7) BSEK. Cumulative return on investment (ROI) at the county level is estimated at 750% (400%) at the county level by 2030 and 1000% (650%) by 2040. ROI for municipal street charging is estimated at 600% (200%) by 2030 and 800% (550%) by 2040. (*Figure 18, Figure 19*)

Total investment cost for all necessary static charging infrastructure at the county level is approximately 8 BSEK, at a levelized cost of 1.4 BSEK/year. Cumulative costs at the county level are estimated at 13 BSEK by 2030 and 31 BSEK by 2040, of which roughly half is OPEX. Total investment cost to build out the recommended levels of on-street static charging within Stockholm Municipality is estimated at 350-400 million SEK, at a levelized cost of 90 million SEK/year including installation, infrastructure, maintenance, grid connections, grid fees, operational overhead and opportunity cost of land use.
(*Table 6, Table 7)*

At 100% car electrification and recommended placement of static charging infrastructure, levelized costs of charging are approximately 0.4-0.5 SEK/kWh for installation, hardware and grid connections and 0.3-0.7 SEK/kWh for electricity. Taxes can add an additional 1.5-1.8 SEK/kWh, for a total cost of 2.5-3.4 SEK/kWh, which corresponds to a petrol or diesel price of approximately 10-12 SEK/litre at the pump. *(Figure 12*)

With current pricing of electricity, static charging is cheapest when it takes place at night. Charging infrastructure is recommended at single-family homes, garages and lots used for night-time parking, and on 10-15% of on-street parking spaces. Significant reductions in the required number of charge points can be achieved with an efficient booking system that distributes access among residents, and can reduce costs particularly for on-street static charging. Fast charging at energy stations is not a default charging method of any passenger car segment in any of the explored scenarios, due to its greater costs. (*Table 4*)

We show that dynamic charging using so-called electric road systems (ERS) can likely provide a majority of the car fleet with all their energy without any need for static charging, at total cost very similar to an equivalent static charging solution. (*Figure 12, page 42*)

ERS installations on major inner-city roads can deliver as much energy to passenger cars as can infrastructure on motorways. (*Figure 16*)

Dynamic (but not static) charging infrastructure could be shared with heavy vehicles to further reduce the cost per user. Other benefits of dynamic charging include greater public sector decision mandate, greater social equality and integration with a potential future national ERS network. However, electric roads suffer from a lack of standards and unclear support at the national level, making such an investment both financially and politically risky for the city. It is possible that electric roads would accelerate the electrification of the car fleet and therefore result in greater cumulative savings, but more research is needed to identify suitable placement and understand interaction effects with static charging. (*page 45*)

Recommendations

The following recommendations for the City of Stockholm are provided based on the results of the analysis. The recommendations are described in greater detail at the end of the report.

1. The city should give greater consideration to speed of implementation than to initial investment cost when comparing strategies for building out charging infrastructure in the city. Every year the transition to EVs is postponed is associated with an opportunity cost of approximately 16 BSEK for Stockholm County, which is twice the total expected installation cost of charging infrastructure.

2. Public investment, subsidies of private investment or raised taxes on fossil greenhouse gas emissions are likely needed if charging infrastructure is to be built out to meet very rapidly increasing demand for charging over the coming years. 95% of charging infrastructure needed to power a fully electrified passenger car fleet should be operational by 2030.
3. Incentives that selectively shorten the average lifespan of cars with internal combustion engines would speed up the overall transition to electric vehicles, with effects beyond the capital region.
4. Powering the growing electric car fleet will result in an increase of total demand for electricity within Stockholm County by approximately 50-70 MW every year until 2030, during the time of day when most charging takes place. This project has not investigated during what time of day it would be most feasible to supply this additional power and the City should explore this further to understand if the proposed plans are compatible with constraints in electricity supply.
5. It is preferable to install static charging infrastructure at locations that result in night-time use. Electricity costs are lower at night and there is likely sufficient capacity within the electrical distribution grid to encompass night-time charging of a fully electrified passenger car fleet, assuming that load-balancing strategies are used to flatten peak loads. Extensive static day-time charging will require capacity upgrades throughout the grid.
6. Operational grid fees make up a substantial part of infrastructure costs. Dynamic grid fees that vary by time of day and by available grid capacity would incentivize installation of charging infrastructure that results in night-time use.
7. Overinvestment in charging infrastructure leads to unnecessarily high costs of charging. We recommend charge points at 10-15% of on-street parking spaces and that an efficient booking system for chargers is introduced that ensures equal access to charging for all users.
8. Very dense charging infrastructure reduces the need for large battery packs in vehicles, resulting in some level of socio-economic cost savings on the fleet side. This project has not quantified these savings and more research is needed to understand if installation of charging infrastructure beyond the recommended levels would result in further cost savings at a system level.
9. City land is expensive and charge points with cable-based interfaces placed along city streets are associated with a high opportunity cost for the required use of attractive land. If charging infrastructure is installed at more than 10% of on-street parking spaces, use of charging interfaces that supply electricity from the parking surface would result in socio-economic cost reductions.
10. Dynamic charging of passenger cars in Stockholm using electric road system technology likely has no cost disadvantage versus static charging, while it has several properties that make it attractive for use in cities. More research should be conducted (in Stockholm or elsewhere) to understand how static and dynamic charging interact and what static charging infrastructure ERS can replace.
11. All calculations, figures and tables are provided in a supplementary Microsoft Excel spreadsheet. The city is advised to continuously revise the parameter assumptions in this spreadsheet as new information becomes available. The spreadsheet can also be used for what-if analysis and to apply the methodology to other cities.

Sammanfattning

Stockholms stad har som mål att möjliggöra elektrifiering av vägfordon för att minska utsläppen av växthusgaser, partiklar och buller från stadstrafiken. Elfordon kräver betydande investeringar i laddinfrastruktur och mycket är fortfarande oklart om var infrastrukturen bäst placeras, vem som bör ha ett investerings- och driftsansvar, samt hur mycket infrastruktur som behövs för att möjliggöra elektrifiering av fordonsflottan.

Forskningsfrågor

Denna rapport bryter ner och jämför interna och externa kostnader förknippade med drift av batteridrivna fordon resp. fordon med förbränningsmotorer, för att uppskatta det totala socioekonomiska värdet av elektrifiering av personbilar. Vi jämför incitament för privata och offentliga aktörer att investera i laddinfrastruktur för personbilar och relaterar dessa till prognostiserad efterfrågan på laddning.

Genom att tillämpa en nätverksmodell som kan hantera interaktionseffekter på Stockholms län identifierar vi uppsättningar av statisk laddningsinfrastruktur som minimerar kostnad över tid, säkerställer lika tillgång till laddning och är tillräckliga för att leverera den nödvändiga energin till en framtida helt elektrifierad bilflotta. Placeringsmodellen är integrerad med kostnadsmodeller för statisk laddningsinfrastruktur, nätrelaterade kostnader och indirekta kostnader. För den föreslagna placeringen och tätheten av laddinfrastruktur, beräknar och jämför vi den resulterande kostnaden (men inte priset) för personbilsladdning. Vi beräknar även om dynamisk laddning med elvägsteknik skulle ge kostnadsbesparingar i förhållande till statiska laddlösningar.

Alla parameterantaganden, beräkningar, tabeller och figurer finns att tillgå i ett kompletterande kalkylark, för att möjliggöra vidareutveckling.

Resultat

Cirka 90 % av trafikarbetet från personbilar i Stockholms län beräknasvara eldrivet till år 2030, om inte långsam utbyggnad av laddinfrastruktur bryter den nuvarande trenden för nyregistrerade fordon. (*Figure 8*)

Nuvarande betydande subventioner av fossilbränsleanvändning i form av underbeskattning av utsläpp av fossila växthusgaser leder till att den offentliga sektorn har ett mycket starkare ekonomiskt incitament än privata aktörer att investera i laddinfrastruktur för elbilar under åtminstone det kommande decenniet. Om utsläppen av växthusgaser inte beskattas i proportion till den samhällsekonomiska kostnad de medför, skulle motsvarande subventioner för elfordon och/eller laddinfrastruktur behövas för att privata och offentliga aktörer ska ha lika incitament att investera i omställningen. Att öka inblandningen av biobränslen i diesel och bensin bidrar till en sådan internalisering, utan att höja kostnaderna på systemnivå för bilar med förbränningsmotorer. Full internalisering kräver ökad beskattning av fossila koldioxidutsläpp, om inte biobränslen blir koldioxidneutrala. (*Figure 4, Figure 18*)

Personbilselektrifiering inom Stockholms län (2,5 miljoner invånare, 1 miljon bilar) kan generera årliga samhällsekonomiska kostnadsbesparingar värda cirka 18 (11)[2] miljarder kr år 2030 och 22 (18) miljarder SEK till 2040. De ackumulerade kostnadsbesparingarna är cirka

[2] Siffror inom parentes exkluderar värdet av minskade obeskattade utsläpp av fossila växthusgaser från bränsleförbränning. Analysen förutsätter en gradvis ökande andel av biobränsleanvändningen i förbränningsmotorbilar och långsamt ökad beskattning av växthusgasutsläpp, vilka tillsammans bidrar till en gradvis internalisering av utsläppsrelaterade kostnader.

100 (50) miljarder kr år 2030 och 300 (200) miljarder kr år 2040. Varje år som övergången försenas eller påskyndas är förknippad med en alternativkostnad på cirka 16 (7) miljarder kr. Kumulativ avkastning på investeringar på länsnivå beräknas till 750% (400%) på länsnivå år 2030 och 1000% (650%) år 2040. Avkastningen på laddning vid gatuparkering i Stockholms kommun beräknas till 600% (200%) 2030 och 800 % (550 %) till 2040. (*Figure 18, Figure 19*)

Total investeringskostnad för all nödvändig statisk laddinfrastruktur på länsnivå är cirka 8 miljarder kr, till en utjämnad kostnad på 1,4 miljarder kr/år. Kumulativa kostnader på länsnivå beräknas till 13 miljarder kr år 2030 och 31 miljarder kr år 2040, varav ungefär hälften är OPEX. Den totala investeringskostnaden för att bygga ut de rekommenderade nivåerna av statisk laddning på gatan inom Stockholms kommun beräknas till 350-400 miljoner kronor, till en utjämnad kostnad på 90 miljoner kronor/år inklusive installation, infrastruktur, underhåll, nätanslutningar, nätavgifter, driftskostnader och alternativkostnad för markanvändning. (*Table 6, Table 7)*

Vid 100 % bilelektrifiering och rekommenderad placering av statisk laddinfrastruktur är utjämnade kostnader för laddning cirka 0,4-0,5 kr/kWh för installation, hårdvara och nätanslutningar och 0,3-0,7 kr/kWh för el. Skatter förväntas tillföra ytterligare 1,5-1,8 kr/kWh, resulterande i en total kostnad på 2,5-3,4 kr/kWh, vilket motsvarar ett bensin- eller dieselpris på cirka 10-12 kr/liter vid pumpen. *(Figure 12*)

Med nuvarande prissättning av el är statisk laddning billigast när den sker nattetid. Laddinfrastruktur rekommenderas vid enfamiljshus, i garage och på parkeringsytor som används för nattparkering och vid 10-15 % av kommunal gatuparkering. Antalet nödvändiga laddpunkter reduceras kraftigt av ett effektivt bokningssystem som fördelar åtkomsten mellan invånarna och kan minska kostnaderna särskilt för statisk laddning på gatan. Snabbladdning vid energistationer är inte en standardladdningsmetod för något personbilssegment i något av de utforskade scenarierna, på grund av högre kostnader. (*Table 4*)

Vi visar att dynamisk laddning med så kallad elväg sannolikt kan förse en majoritet av bilparken i länet med all sin energi utan behov av statisk laddning, till en kostnad nära den för motsvarande statisk laddinfrastruktur. (*Figure 12, s. 42*)

Elvägsinstallationer på stora innerstadsvägar kan leverera lika mycket energi till personbilar som infrastruktur på motorvägar. (*Figure 16*)

Dynamisk (men inte statisk) laddinfrastruktur skulle kunna delas med tunga fordon för att ytterligare minska kostnaden per användare. Andra fördelar med dynamisk laddning inkluderar större offentligt beslutsmandat, större jämlikhet och integration med ett potentiellt framtida nationellt elvägsnät. Elvägar lider dock av bristande standarder och otydligt stöd på nationell nivå, vilket gör en sådan investering både ekonomiskt och politiskt riskabel för Stockholm. Det är möjligt att elvägar skulle påskynda elektrifieringen av bilparken och därför resultera i större besparingar över tid, men mer forskning krävs för att identifiera lämplig placering och förstå interaktionseffekter med statisk laddning. (*s. 45*)

Rekommendationer

Följande rekommendationer till Stockholms Stad lämnas utifrån resultaten av analysen. Rekommendationerna beskrivs mer utförligt i slutet av rapporten.

1. Stockholm bör lägga större vikt vid genomförandehastighet än initial investeringskostnad när man jämför strategier för att bygga ut laddinfrastruktur i staden. Varje år som övergången till elbilar skjuts upp är förknippad med en alternativkostnad på cirka 16 miljarder kr för länet, vilket är dubbelt så mycket som den totala förväntade installationskostnaden för laddinfrastruktur.

2. Offentliga investeringar, subventioner av privata investeringar eller höjda skatter på fossila växthusgasutsläpp behövs sannolikt om laddinfrastruktur ska byggas ut tillräckligt snabbt för att möta ökande efterfrågan på personbilsladdning under de kommande åren. 95 % av den laddinfrastruktur som krävs för att försörja en helt elektrifierad personbilsflotta med el behöver vara i drift 2030.
3. Incitament som selektivt förkortar den genomsnittliga livslängden för bilar med förbränningsmotorer skulle påskynda den totala övergången till elfordon, med effekter utanför huvudstadsregionen.
4. Den växande elbilsflottan kommer att resultera i en ökning av total efterfrågan på el inom Stockholms län med cirka 50-70 MW varje år fram till 2030, under den tid på dygnet då mest laddning sker. Vi har inte undersökt under vilken tid på dygnet det skulle vara lättast att tillföra denna effektproduktion och staden bör undersöka detta ytterligare för att förstå om de föreslagna planerna är förenliga med begränsningar i elförsörjningen.
5. Det är fördelaktigt att installera infrastruktur för statisk laddning på platser som leder till nattlig användning. Elkostnaderna är lägre på natten och det finns sannolikt tillräcklig kapacitet inom eldistributionsnätet för att täcka nattladdning av en helt elektrifierad personbilsflotta, förutsatt att lastbalanseringsstrategier används för att jämna ut topplaster. Omfattande statisk laddning dagtid skulle kräva kapacitetsuppgraderingar i hela nätet.
6. Löpande nätavgifter utgör en betydande del av infrastrukturkostnaderna. Dynamiska nätavgifter som varierar beroende på tid på dygnet och tillgänglig nätkapacitet skulle uppmuntra till installation av laddinfrastruktur som resulterar i användning nattetid.
7. Överinvesteringar i laddinfrastruktur leder till onödigt höga kostnader för laddning. Laddplatser rekommenderas vid 10-15 % av gatuparkeringarna och ett effektivt bokningssystem för laddare rekommenderas att införas för att säkerställa lika tillgång till laddning för alla brukare.
8. Mycket tät laddningsinfrastruktur minskar behovet av hög batterikapacitet i fordon, vilket bör minska kostnadsposten för fordon i den samhällsekonomiska kalkylen. Vi har inte kvantifierat dessa besparingar och mer forskning behövs för att förstå om installation av laddinfrastruktur utöver de rekommenderade nivåerna skulle resultera i ytterligare kostnadsbesparingar på systemnivå.
9. Markyta i staden är dyr och laddpunkter med kabelbaserade gränssnitt placerade längs stadsgator är förknippade med en hög alternativkostnad för nyttjande av attraktiv mark. Om laddinfrastruktur installeras på mer än 10 % av gatuparkeringsplatserna skulle användning av laddgränssnitt som levererar el från markytan resultera i samhällsekonomiska kostnadsminskningar.
10. Dynamisk laddning av personbilar i Stockholm med elvägsteknik blir sannolikt inte dyrare än statisk laddning, samtidigt som tekniken har flera egenskaper som gör den attraktiv att använda i städer. Fortsatt forskning rekommenderas (i Stockholm eller någon annanstans) för att förstå hur statisk och dynamisk laddning samverkar och vilken statisk laddningsinfrastruktur elvägar skulle kunna ersätta.
11. Alla beräkningar, figurer och tabeller finns i ett kompletterande Microsoft Excel-kalkylblad. Staden rekommenderas att kontinuerligt revidera parameterantagandena i detta kalkylblad när ny information blir tillgänglig. Kalkylarket kan också användas för what-if-analys och för att tillämpa metoden på andra städer.

Introduction

Background

The City of Stockholm seeks viable strategies to reduce greenhouse gas and other emissions from road traffic. In the passenger car segment, electrification is considered key and in discussions with the city, electrification of 50% of the passenger car traffic in the city by 2030 has been considered to be a target with broad acceptance. We will later see that this is likely a great underestimate. The rate of electrification varies greatly within the city and cars parked on city streets in areas with apartment buildings have turned out to be particularly challenging to electrify.

Proposals have been made to equip all parking spaces on city streets and in public parking garages with static charging infrastructure. Opponents argue that such plans are too expensive, unnecessary, or that chargers do not belong on streets and should instead be placed at large workplace parking lots, in garages and at single-family homes where they do not interfere with other uses of land. Such interference includes obstruction of snow clearing and street cleaning, reduced mobility for the vision impaired, pedestrians and cyclists, reduced bicycle parking, reduced opportunities for outdoors restaurant seating, increased costs of other sub-surface work, destruction of tree roots, and impact on culturally significant sites.

Meanwhile, private investment in charging infrastructure is not keeping pace with the city's targets. Stockholm Municipality aims to have 4000 public chargers installed at on-street parking spaces and in public garages by year 2023, with 1600 installed as of November 2021, mainly in public garages where the city itself invests. Interest from private actors to invest in chargers for on-street parking has been lower than anticipated, with high cost and lack of available power grid capacity claimed to be major bottlenecks. Private investors are reported to frequently abandon sites that otherwise seem promising for charger installation after learning about costs and capacity limitations related to the electrical grid. Private interest in investing in areas outside of the city centre have also been low, in particular in areas with lower median income.

The challenges are not unique to Stockholm and in parallel[3], the city has surveyed the strategies of several other European cities. This research complements those efforts by looking at local conditions and opportunities through a quantitative lens.

Research Questions

The central aim of this report is to identify what Stockholm Municipality can and must do to enable all inner-city traffic with passenger cars to be electric by year 2030.

Several related questions are also explored. We begin by estimating the socio-economic value of electrification of passenger cars, per year and cumulative, to understand how much charging infrastructure can cost before electrification no longer results in overall cost savings. The report also answers whether and for whom sufficient financial incentives are in place to drive the transition to emission-free passenger car traffic.

All cars in the region are eventually expected to be electrified. This means that the total energy needed to power the fleet per unit of time will be fixed and independent of the type and placement of charging infrastructure used to transfer that energy to the cars. For the geographic

[3] Public Charging Deployment Models in European Cities, Including Insights and Proposals for the City of Stockholm. Stockholms stad, 2021.

region of Stockholm County, we try to identify the cheapest set of infrastructure that is sufficient to deliver this fixed amount of energy to a future fully electrified fleet of cars. In addition to minimizing cost, we strive for social equality by seeking solutions that ensure equal access to charging at equal cost, throughout all geographic areas and income groups in the region. Some solutions can also be associated with regulatory challenges or high externalized costs, which we want to avoid.

This research explores three strategies for minimizing total cost of charging: 1) placement that results in high and even utilization; 2) reducing excessive redundancy; and 3) using novel non-intrusive charging interfaces to avoid further waste of scarce land in densely populated areas.

The following additional strategies have been identified but not further explored: 4) optimizing for hyperlocal variations in cost-driving factors, such as subsurface congestion (pipes, cables, roots, basements, subway, etc.), distance to grid access points and conflicting use of land surface; 5) technical solutions to reduce cost within sites, such as local energy storage, novel excavation techniques, joint scheduling with other city maintenance, or reuse of present or past connections to the electricity grid; 6) minimizing future capital destruction by anticipating where changes to the city plan are likely to occur in the future; and 7) various ways of reducing total car use.

Methodology

The research questions are investigated through quantitative data analysis using a custom built model, summarized in Figure 1, with key figures and tables from the report indicated at each calculation step. Separate chapters describe:

- Calculation of the value generated from electrification of passenger cars due to gradually increasing cost benefits of battery-electric cars versus internal combustion engine cars;
- Calculation of the rate of charging infrastructure deployment required to continue the rapid increase in market share of electric passenger cars;
- Calculation of what density of static chargers per type of location (e.g. on-street parking and at workplaces) that would minimize total cost, while ensuring reliability and equality, as well as what cost of charging this would result in;
- Exploration of how a solution using dynamic charging using so-called electric road-technologies would perform in comparison to if only static charging is installed;
- Annual and cumulative socio-economic result calculation based on all of the above.

Calculations are generally based on mean values for large populations and qualitative sensitivity analyses are provided where applicable to understand how variation within the population can result in a spread of outcomes for different individuals.

The calculations were implemented in a Microsoft Excel spreadsheet, enclosed with this report as supplementary material. This spreadsheet can be used to apply the same methodology to other geographic regions or to explore changes in outcome with other assumptions about the many input parameters. Model parameters used within the report represent conditions in and around Stockholm, Sweden, for the time period 2020-2040.

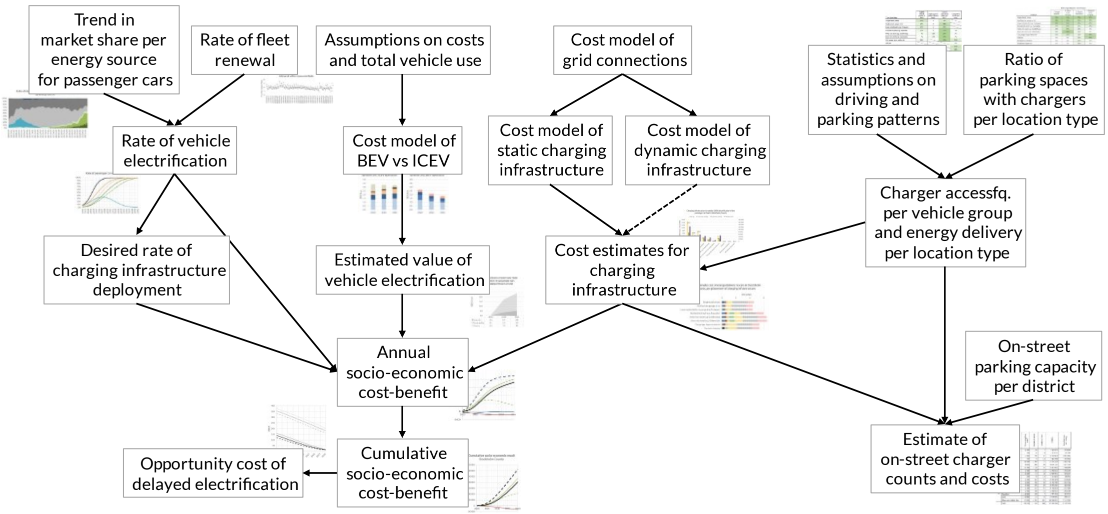

Figure 1. Flowchart of the data analysis behind this report.

Value of Passenger Car Electrification

Electrification of the city's fleet of passenger cars is motivated by an assumption that this would be socio-economically beneficial. We quantify beneficial as that the total (internalized plus externalised) levelized cost of operating the system will be lower if future cars are electric than if those cars run on internal combustion engines. Internalized cost components that are assumed to change significantly through electrification are the upfront and maintenance cost of vehicles, the cost of energy carries and the cost of their distribution infrastructure. Externalized cost components are primarily emissions and land use.

Vehicle insurance costs and taxes not tied to emissions have been excluded from the calculations due to assumptions that these values will remain unaffected by vehicle electrification[4].

The calculations here do not account for that electrification reduces traffic noise on roads with low vehicle speeds (tire friction noise dominates over engine noise at high speeds). Traffic noise has a documented effect on housing prices, human health, wildlife behaviour and indirectly on whole ecosystems influenced by wildlife behaviour. ASEK 7.0[5] notes a cost of passenger car noise in urban areas of 0.164 SEK/km, but electrification would only partially reduce this. The socio-economic value of the impact from noise on ecosystems is unknown to us. Furthermore, the calculations omit costs of emissions associated with manufacture of vehicles and batteries, as well as costs of emissions other than greenhouse gases. $PM_{2.5}$ and NO_x emissions are produced from fuel combustion and these are expected to decrease slowly over time even without electrification due to tighter regulations applying to new ICEVs. PM_{10} particles are primarily produced from wear of tires and brake pads and there are indications that electrification will increase these, as EVs typically have greater torque and weight than ICEVs.

Difference in Socio-Economic Cost, ICEV vs. BEV

It is beyond the scope of this report to fully model the total socio-economic cost of passenger car use. Our ambition is instead to model the *difference* in socio-economic cost of a system with battery electric vehicles (BEVs) vs. one with internal combustion engine vehicles (ICEVs). The words system cost and socio-economic cost are used interchangeably.

Our model of system cost of an ICEV includes:

1. vehicle purchasing cost,
2. repair and maintenance costs,
3. fuel costs[6],
4. taxes on fuels tied to greenhouse-gas (GHG) emissions,
5. the additional untaxed cost of GHG emissions.

Our model of BEV system costs includes:

1. vehicle purchasing cost, excluding battery pack,

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[4] May not be entirely true. Insurance costs may scale either with vehicle purchase cost, or with the costs of repairs and maintenance. It is not clear how non-emissions related taxes that are collected via fuel sales will be transferred to EVs, thus they have been assumed to remain unchanged.
[5] Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0. Trafikverket, 2020.
[6] The overhead cost of distribution infrastructure for combustion engine fuels has not been modelled explicitly, but are included in the fuel price.

2. battery pack cost,
3. repair and maintenance costs,
4. electricity costs,
5. cost of infrastructure needed to delivery electricity to the vehicle.

Assumed parameter values and calculations to estimate each of these model component can be found in the supplementary model spreadsheet. Infrastructure costs are further explained in the next chapter.

Figure 2 shows the cost development for each type of vehicle, using parameter assumptions for costs and vehicle operation set to be representative of Stockholm municipality. We see that increased costs of fuel, partly from increased use of biofuels and partly from increased taxation of emissions, are expected to drive up the internalized costs of ICEVs. However, when accounting for the externalized costs of emissions, the ICEV system cost remains effectively unchanged throughout the forecast time period. Values of 7 SEK/kg CO_2-eq and 3.44 kg/litre fossil diesel (well-to-wheel) are used to calculate the cost of emissions, while biofuels have lower fossil emissions that also decrease over time. Greenhouse gas emissions from use of electricity are negligible in the Swedish power grid. The Swedish valuation of the social cost of carbon, our inclusion of well-to-tank emissions and carbon-neutral local electricity together result in much greater emissions-related cost differences between BEVs and ICEVs than in most international studies.

Electric drivelines are much less complex than combustion engine drivelines, yet we note that as of 2020, BEVs are sold at prices equivalent to the combustion engine equivalent, after deduction of the cost of a replacement battery pack. This suggests that many current BEV options are retrofits of already developed ICEV platforms, rather than vehicles originally designed to be electric. As seen in Figure 2, the purchase and maintenance costs of BEVs are forecast to decline, due to improvements in battery technology, increased sales volumes of BEVs (economies of scale), and dedicated or maturing EV platforms.

Operational expenses (repair, maintenance and fuel/energy) are expected to be very low for BEVs in comparison to ICEVs. The cost of energy delivery (installation and maintenance of charging infrastructure and grid connection fees) remains to be determined later in this report and will vary depending on the infrastructure’s type, placement and utilization.

Levelized costs associated with the initial purchase of the vehicle will be lower than in Figure 2 for vehicles with greater annual mileage than the average passenger car. This makes BEVs particularly suited for commercial applications, e.g. as taxis and rental cars, for which operational costs dominate.

These cost differences in SEK/km, SEK/kWh and SEK/car-year are shown in Figure 3, Figure 4 and Figure 5, respectively. In these figures and throughout the report, the inner city is a subset of the municipality, which is a subset of the county. Model parameters differ slightly between the regions, with the primary impact on these figures coming from that cars are assumed to have a greater annual distance the further they are based from the city centre. Other differences that have minor impact are driving patterns that result in lower energy consumption at lower average speeds and differences in average car models, including battery capacity. We refer to the supplementary spreadsheet for details.

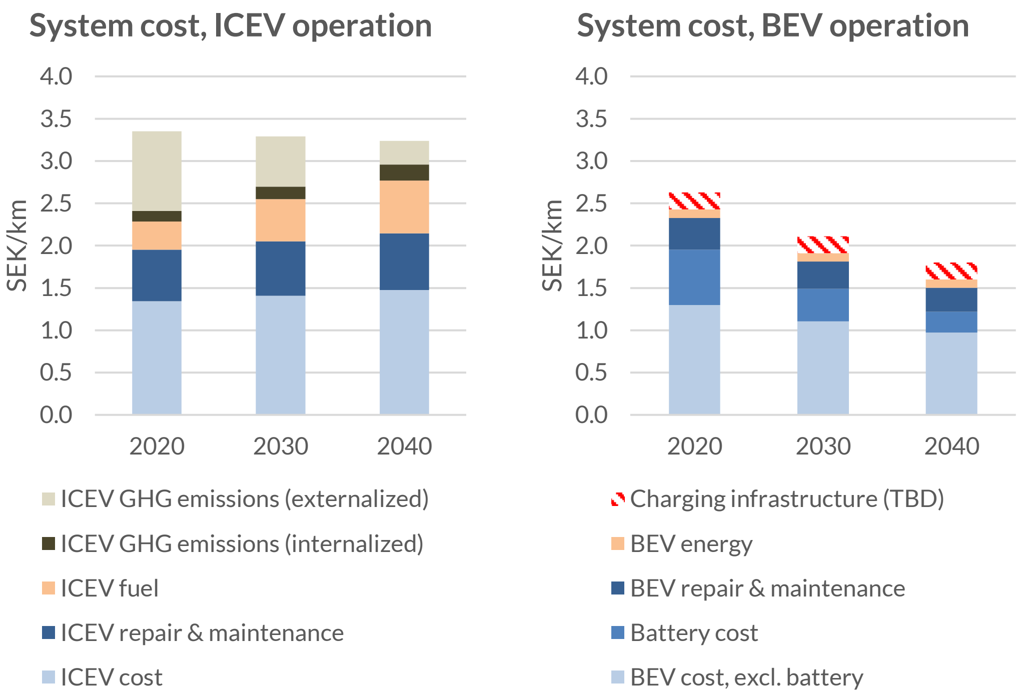
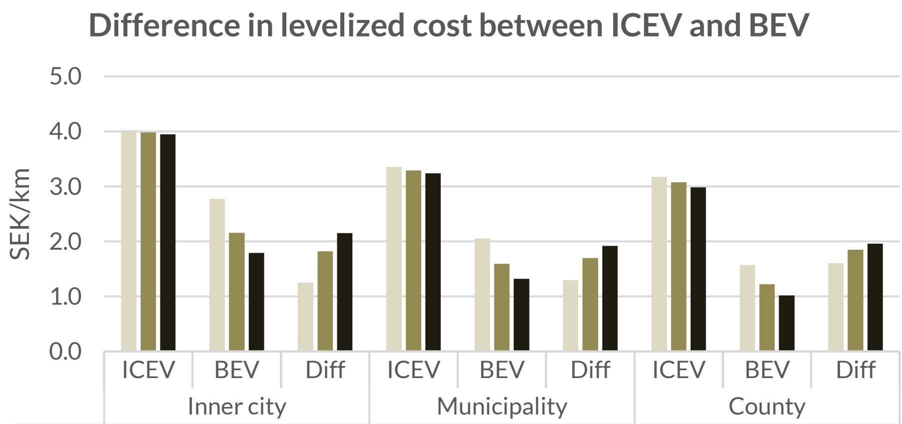
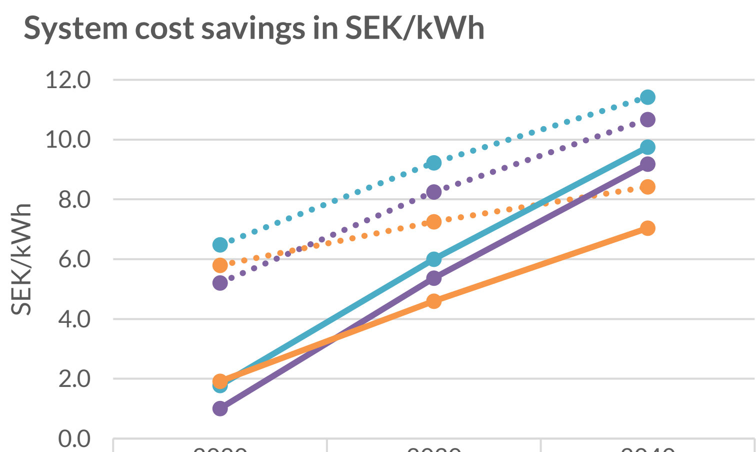


Figure 2. Modelled system cost of vehicle utilization, for internal combustion engine vehicles (ICEVs) and battery-electric vehicles (BEVs). All costs that are assumed to be unaffected by the method of propulsion have been excluded from the model, thus real costs are higher for both vehicle types. The cost of charging infrastructure will be estimated later in this report, and pricing of charging (i.e. user cost) will be subject to market forces. The illustrative cost of charging infrastructure of 0.2 SEK/km corresponds to approximately 1 SEK/kWh. Internalized greenhouse gas (GHG) emissions are those paid for through emissions-related taxation of fuels. Significant subsidies of the ICEV system in the form of undertaxation of GHG emissions mean that private sector investors do not reap the full benefits of electrification. Parameter values used in the figure are for Stockholm municipality. Taxes unrelated to emissions are assumed to be unaffected by the transition are have been excluded, as have explicit subsidies of EVs.



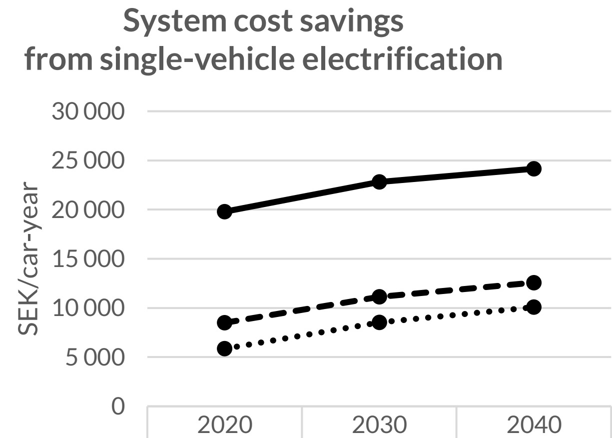
	Inner city			Municipality			County		
	ICEV	BEV	Diff	ICEV	BEV	Diff	ICEV	BEV	Diff
2020	4.0	2.8	1.3	3.4	2.1	1.3	3.2	1.6	1.6
2030	4.0	2.2	1.8	3.3	1.6	1.7	3.1	1.2	1.9
2040	3.9	1.8	2.2	3.2	1.3	1.9	3.0	1.0	2.0

Figure 3. Difference in levelized system cost between ICEV and BEV, in SEK/km, excluding the cost of charging infrastructure and parking and including the externalized cost of GHG emissions. Bar height in this figure is the same as the total for each year and vehicle type in Figure 2. Model parameters differ slightly between the regions, with the primary difference being that cars are assumed to have a greater annual distance the further they are based from the city centre. The inner city is a subset of the municipality, which is a subset of the county.



	2020	2030	2040
Inner city (system)	5.2	8.3	10.7
Municipality (system)	6.5	9.2	11.4
County (system)	5.8	7.3	8.4
Inner city (internalized)	1.0	5.4	9.2
Municipality (internalized)	1.8	6.0	9.8
County (internalized)	1.9	4.6	7.0

Figure 4. Difference in levelized cost between ICEV and BEV, in SEK/kWh (BEV) and excluding the cost of charging infrastructure. The magnitude of the per-kWh cost savings gives an indication of what charging infrastructure can cost if the transition should still result in overall cost savings on a system level. Lines labelled “system” include the externalized cost of GHG emissions.



	2020	2030	2040
Inner city	5 855	8 528	10 073
Municipality	8 492	11 126	12 574
County	19 788	22 800	24 155

Figure 5. Total annual system cost reduction from electrification of a single vehicle, including the externalized (untaxed) cost of GHG emissions and excluding the cost of charging infrastructure. Vehicles based in urban areas are assumed to drive shorter annual distances than the average vehicle within the county, resulting in smaller annual savings for urban vehicles.

Sensitivity Analysis

The numbers presented here are calculated based on estimated means for the vehicles making up the different car populations. However, numbers for individual vehicles can differ quite significantly from these and are sensitive to several interacting factors.

Low speed stop-and-go vs. high stable speed: Electric vehicles can recoup energy while braking, which substantially reduces energy consumption of city driving. At high and stable speeds, energy costs are dominated by road friction and air resistance, which cannot be recovered. The result is that the energy consumption per km of a BEV is around 40% lower in city driving than on open roads, while the opposite is true for ICEVs. Thus, per-km savings on fuel/energy costs are much greater for vehicles primarily used within cities than for vehicles used primarily on open roads.

Low vs. high mileage: Affects the OPEX vs. CAPEX ratio in the current model, as the three vehicle populations have been modelled with per-car lifespans partly limited by calendar time (and partly by total driven distance). With the current model, inner-city vehicles have the greatest costs per km and per kWh.

Basic vs. premium car models: Premium cars cost more to purchase and maintain, but they do not necessarily have greater energy consumption. This means that fuel/energy costs make up a smaller share of the total cost of premium car models than basic car models. The relative contribution of battery capacity to car sales price is also smaller for premium car models, thus these models are more likely to be sold with high battery capacities. This means that we are likely to first see electric cars in the premium market segment. It also means that basic car models will be more range limited, and that the basic model segment has greater requirements on charging infrastructure in terms of density and ease of access. The maximum power input (and output) of a battery pack is proportional to its capacity, which means that battery packs of all sizes can be charged from empty to full in the same time span. This also implies that the premium car segment has greater requirements on charging infrastructure in terms of available power per vehicle.

Light vs. heavy cars: Among sampled electric car models, SUVs in general have greater energy consumption than light vehicles (e.g. 24.4 kWh/km for a Volvo XC40[7] vs. approximately 16.3 kWh/km for small BEVs[8]), but exceptions exit (e.g. the Hyundai Kona Electric SUV with 16.0 kWh/km). Sampling of a few representative vehicle models indicates that fuel consumption is approximately double for light ICEVs than ICE SUVs. As energy consumption of electric cars is reported to differ so much between models, there are no clear conclusions regarding how car weight affects total costs.

2020 vs. 2040: With time, BEV CAPEX is projected to decrease and the battery pack's relative influence on the car price is expected to become smaller. This particularly affects basic car models, for which the battery initially makes up a larger part of the vehicle cost than for premium models. Larger battery packs become more feasible, allowing for more powerful motors, lower density of charging infrastructure and ICEV OPEX is increasingly internalized.

BEV vs. PHEV: Although we have opted to model only ICEVs and BEVs, plug-in hybrid electric vehicles (PHEVs) are the most common type of electric vehicle in Sweden as of 2021. A possible reason for the popularity of PHEVs in Sweden is a still-low charger density along rural parts of the road network. Most of Sweden's area is rural and though most car trips may be urban, it is likely safe to assume that most cars are occasionally used in rural settings. Battery capacity has so far been too costly for BEVs to be equipped with battery packs large enough to prevent range anxiety. We assume that declining battery costs, increased density of charging infrastructure and increased costs of combustion engine fuels will eventually make BEVs the standard, and that PHEV is a transitional technology.

Summary

Electrification of passenger cars can greatly reduce the system-level cost of operating the transport system, with per-vehicle savings increasing rapidly over time. From a pure cost perspective, the transition to EVs is driven both by decreasing costs for BEVs and increasing costs for ICEVs. The cost decline for electric vehicles is driven by a high rate of technology development as well as growing sales volumes for EV models. The cost increase of ICEV operation is caused primarily by internalization of externalized costs that are already present in the system: a gradual replacement of fossil fuels with bio-fuels and increased taxation of remaining fossil GHG emissions. Neither bio-fuels nor GHG taxation affect the system-level cost of ICEVs.

Break-even was reached for the average vehicle around model year 2015 if externalized GHG emission costs are included, and will be reached in the early 2020s for internalized costs alone. Break-even is not reached in the same year for all vehicles and those to first reach cost parity are premium vehicles operated in urban traffic with high annual mileage. In later model years, electrification becomes a cost saver also for owners of basic-segment vehicle models, operating primarily outside of cities and with lower annual mileage. That charging infrastructure has high density and accessibility is of greater importance to owners of cheaper vehicle models, which are expected to be equipped with smaller battery packs than premium vehicles and therefore need to be charged more often.

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[7] Bilens certifierade värden för räckvidd och elförbrukning, https://www.volvocars.com/se/support/manuals/xc40-recharge-pure-electric/2020w37/specifikationer/specifikationer/bilens-certifierade-varden-for-rackvidd-och-elforbrukning

[8] Elbilar 2020 – här är bilarna som drar minst i Sverige, https://tibber.com/se/magazine/inside-tibber/elbilar-2020-dessa-drar-minst

Estimating the Rate of Passenger Car Electrification

The previous section estimated the cost saving potential, at system level, resulting from electrification of *all* passenger cars. At present, fully electric cars still make up a small minority of all cars on the roads in and around Stockholm. But how small, and how quickly can this ratio be expected to grow?

Data for Stockholm county on new vehicle registrations by energy source[9], as well as total number of vehicles in use[10], are available from Statistics Sweden. Using this data, we get monthly point estimates of the number of years vehicles in the region remain in use, estimated as $years\_in\_use = population\_size/12 * new\_vehicles\_per\_month$.

Figure 6 shows that this value has remained stable around ten years for the past 15 years, i.e. approximately 10% of the passenger car fleet is replaced every year. Replaced vehicles can be scrapped or sold on to be used elsewhere.

As seen in Figure 7, a transition away from ICEVs and towards EVs is taking place, with BEVs, PHEVs and HEVs together making up around 60% of the new registrations in 2021. BEVs alone have gone from <1% to >10% between 2018 and 2021. The data show a high and rising demand for EVs. Given that our models showed cost parity on average around 2020 for BEVs and ICEVs, we speculate that most buyers of hybrid vehicles would have opted for a BEV if they perceived charging infrastructure to be ubiquitous. If this assumption is true, the future ratio of EVs that are fully electric will be controlled by the rate at which charging infrastructure is built out.

The trend of new registrations of BEVs is forecast using a so-called S-curve subjectively fitted to the historic data (Figure 7 and Figure 8). By this projection, 90% of newly registered vehicles in Stockholm county will be BEVs or PHEVs used primarily in electric mode by 2026.

Using the information that vehicles remain in use in Stockholm for approximately ten years, the cumulative fleet composition can be calculated. We do this by assuming vehicles are retired after a normally distributed time, with mean ten years and standard deviation two years (95% within 6-14 years). As seen in Figure 8, this results in an estimate of 65% BEVs in the fleet by 2030, with the remainder being >90% PHEVs. The prediction is fairly sensitive to under- or overestimations of both the ratio of new registrations and the vehicle replacement rate, but the actual BEV ratio in 2030 is likely to fall within the 50-80% range, with >95% of vehicles being capable of charging.

Given that EVs already make up such a large and increasing ratio of new registrations, policy instruments designed to incentivize early retirement of ICEVs would likely be a very effective way to quickly reach >95% EVs on the roads.

[9] Nyregistrerade personbilar efter län och kommun samt drivmedel. Månad 2006M01 - 2021M08 http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__TK__TK1001__TK1001A/PersBilarDrivMedel/
[10] Fordonsbestånd 2001–2020 https://www.scb.se/hitta-statistik/statistik-efter-amne/transporter-och-kommunikationer/vagtrafik/fordonsstatistik/pong/tabell-och-diagram/fordonsbestand/

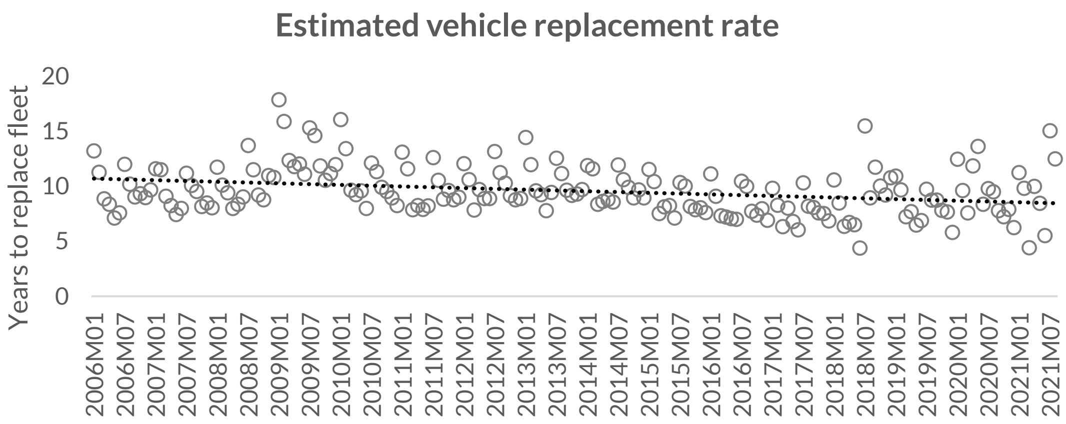


Figure 6. Estimated number of years that passenger cars remain in use in the Stockholm region, calculated based on monthly data of new registrations and total number of vehicles in use.

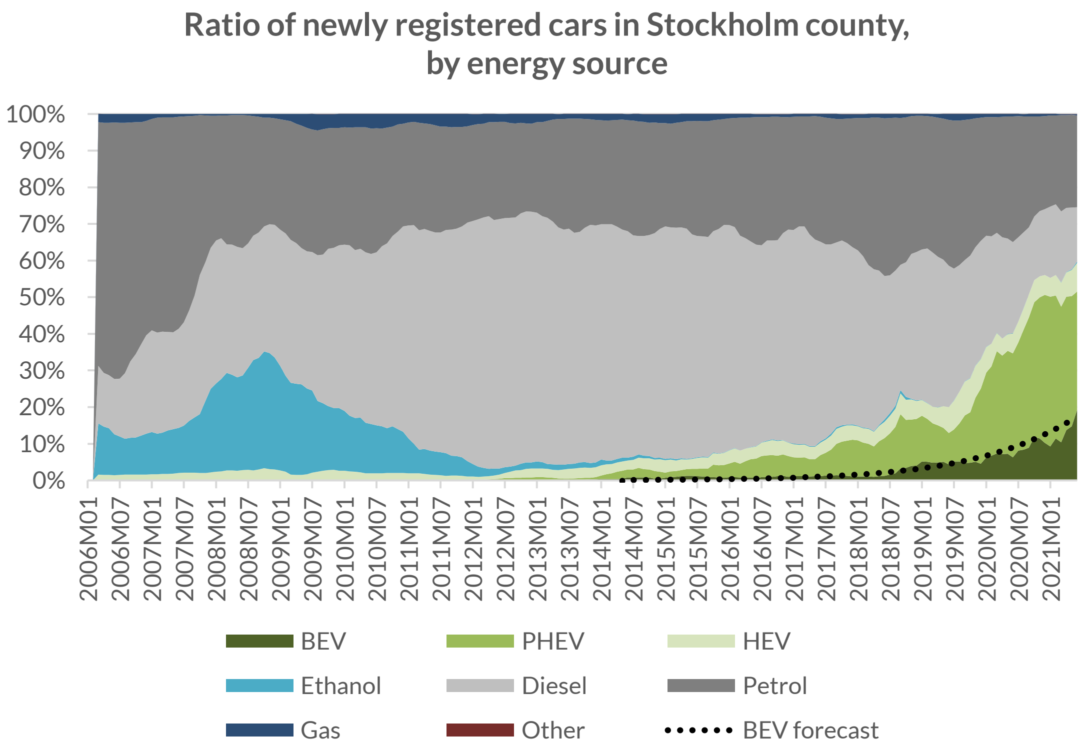


Figure 7. Ratio of newly registered cars in Stockholm county, by energy source. The data have been smoothed using a five-month rolling average.

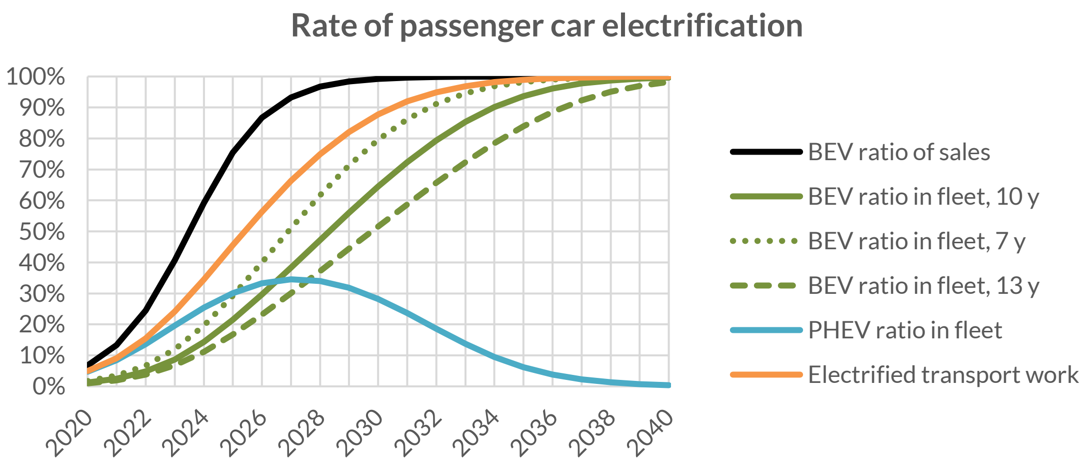


Figure 8. Predicted rate of electrification of the Stockholm county fleet of passenger cars. The BEV ratio of new car registrations will be influenced by the placement, density, type and speed of deployment of charging infrastructure within the region. The time lag between when BEVs make up >90% of new registrations to when BEVs make up >90% of vehicles in use is driven as much by how many years ICEVs remain in use as by their ratio of sales.

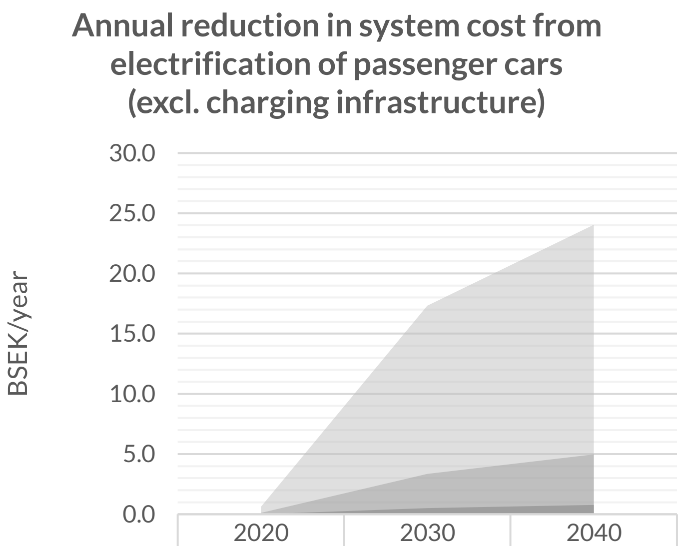
Value of Electrifying All Resident Vehicles

Multiplying the per-vehicle cost savings from Figure 5 with the number of vehicles and the ratio of electrified transport work from Figure 8, we get a forecast (Figure 9) of the value generated by electrification of passenger cars in the region. Fleet sizes are approximations based on current population sizes, adjusted for forecast population growth, and current vehicle ownership rates; values used are 77 000 cars for the inner city, 396 000 cars for the municipality and 997 500 cars for the county, for all years.

PHEV sales are modelled by applying the same sales ratio curve as BEV, offset two years earlier, to the remainder of non-BEV sales. PHEVs are assumed to be operated 70% in electric mode and contribute half the value of BEVs per km.

The forecasting model gives a slight over-estimation of the annual cost savings, as per-car values are for new cars sold in that year. A more accurate model would use fuel and energy costs from the year of forecasting, but vehicle costs from each vehicle's year of manufacture.

The rapid electrification of passenger car traffic results in an equally rapid decrease in demand for combustion engine fuels from passenger cars within Stockholm County. Limited supply is sometimes claimed to prevent extensive use of biofuels (in Sweden) or electrofuels (most of Europe), but due to electrification, even a ramped increase from present levels to 80% renewables by 2030 and 100% by 2040 would only result in a very minor increase above present consumption, that peaks before 2025.



	2020	2030	2040
Inner city	0.0	0.5	0.8
Municipality	0.1	3.4	5.0
County	0.6	17	24

Figure 9. Predicted annual system-level savings generated by electrification of passenger cars (PHEV and BEV), in Stockholm inner city, municipality and country. Savings, in billion SEK/year, are excluding the cost of charging infrastructure. The inner city is a subset of the municipality, which is a subset of the county.

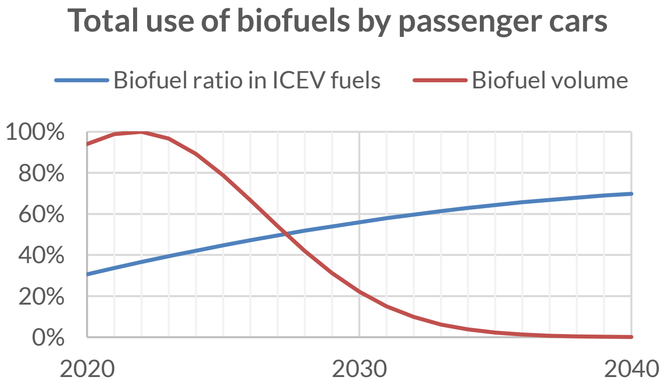


Figure 10. Despite forecast increases in the ratio of biofuels mixed into ICEV fuels, the total demand for biofuels is not forecast to increase, due to rapid electrification of the car fleet.

Static Charging Infrastructure

Static charging infrastructure refers to all methods of delivering energy to a vehicle that require the vehicle to remain stationary during energy transfer. This section describes different technologies available for static charging, locations where this infrastructure can be placed, resulting patterns of utilization and different pros and cons with each. The section concludes with cost estimates for static charging sufficient to electrify Stockholm's fleet of passenger cars.

Technologies and Placement Alternatives

The dominant solution for vehicle charging today is static charging via cable. Static in this context refers to that the vehicle is stationary, as opposed to dynamic, where the vehicle charges while moving. Though relatively homogeneous in theory, the market is still fragmented by incompatible payment solutions, brand lock-in and incompatible outlet types. As of 2021 efforts are being made to reduce this fragmentation through regulation.

The hardware to which the cable is connected comes in many forms, including poles servicing 1-4 adjacent parking spaces, bollards that can be lowered into the ground, long horizontal bar solutions that keep cabling above ground and that stretch across several parallel parking spaces, outlets installed directly in the ground, or arms extending from adjacent walls that can reach across sidewalks. The different solutions all have different pros and cons that make them more or less suited to different physical environments where charging is to be installed.

Cable interfaces are not the only solutions for static charging. The same technologies that enable dynamic charging can also be used while the vehicle is stationary. These include conductive or inductive interfaces installed in the road surface, conducive energy transfer from the side, and overhead catenary cables (thus far only demonstrated for heavy vehicles). Conductive interfaces are capable of transferring greater power, while inductive interfaces require less maintenance and are less intrusive in the physical environment. Most of these solutions have been deployed for static charging either commercially or in pilot scale, but the market share is so far very small compared to cable interfaces. To the best of our knowledge, none of the interfaces developed for dynamic charging have so far been used for public charging of passenger cars. Electric vehicles already in use can likely be retrofit with these charging interfaces, should they become more popular.

Like parking itself, placement of hardware for static charging of passenger cars provides different advantages and disadvantages for different stakeholders depending on where it is installed. A qualitative comparison of different placement alternatives is provided in Table 1.

Placement	User perspective	Operator perspective	Non-user impact
Single-family home	Attractive to have access to an overnight charger at home. Full control over installation. Existing grid connection can be used. Charging power if a car is charged regularly and slowly in 12 hour sessions is proportional to the power used when vacuum cleaning (around 1.5 kW). Vehicles may have a greater minimum charging power than this (3.7 kW is common today), which complicates load balancing in city districts with many single-family homes.	From a grid perspective, it is very important that not all cars in an area of this type start charging at maximum power when they all come home from work. There is likely sufficient unused district grid capacity at night to let all cars charge, if the energy is distributed over the entire night.	No significant impact.
Garage or lot (residential)	Residents appreciate the convenience of access to charging at home. Reserved parking spaces necessitate outlets at every space, which guarantees charger access but raises cost of charging. Existing grid connections can often be used, in particular if only a handful of cars need to be charged simultaneously.	Long-lasting parking sessions and many simultaneously parked cars make predictive load balancing strategies both important and relatively easy to implement. Reserved parking can lead to low utilization per outlet. Low risk of vandalism and no weather exposure in garages.	Association members without cars (or with ICEVs) may oppose investment in chargers using shared funds. Others may see it as a value-adding investment for the future.
Street parking in residential areas	Convenient to have access to charging at home. Important to minimize search traffic upon returning home, and to be able to leave the car during days when it is not needed. If not all parking spaces are equipped with chargers, access must somehow be distributed between all residents to prevent that those who return home later than others also can charge their cars.	Long parking sessions (10-100 hours) make it difficult to achieve high utilization of installed infrastructure. Difficult to average more than one charging vehicle per day per charge point.	Any cars not in need of charging still want unhindered access to parking, which competes with charger accessibility. Undesirable to sacrifice sidewalks, bicycle paths or park area for car charging.

<table>
<tr><td>Street parking in mixed residential and commercial areas (inner and outer city)</td><td>Residents appreciate the convenience of access to charging at home, but incentives designed to increase parking turnover can make parking much less convenient if charging infrastructure is dense. Many (most?) day-time visitors do not park here regularly and chargers here are insufficient to enable their transition to BEV from ICEV.</td><td>Site with high parking lot occupancy all-day round and potentially high turn-over. Can expect perhaps one charging session overnight and three shorter sessions in day-time. Residents that leave their vehicles unused in day-time cut into profits. Desirable to have incentives in place to increase turnover.</td><td>Cables and charging poles restrict the movement of pedestrians, in particular those who are vision or mobility impaired. Some businesses appreciate attractive parking nearby, while some restaurants and cafés would like to use the land for seating. Car parking already occupies significant land and city planners are hesitant to invest in infrastructure that further permanents this land use. More cables underground increase the cost of other maintenance to the city.</td></tr>
<tr><td>Large public parking garage</td><td>Many (most?) day-time visitors come here irregularly and chargers here are insufficient to enable their transition to BEV from ICEV. Residents and regular parkers can electrify. Can complement and possibly reduce demand for shared chargers elsewhere.</td><td>Site with high parking occupancy in daytime, with potential for high turn-over and high night-time occupancy. Can expect perhaps one charging session overnight and three shorter sessions in day-time. The garage owner wants to maximize occupancy while the charger operator wants to maximize turnover. Minimal weather exposure and low risk of vandalism.</td><td>Non-charging vehicles have fewer parking options if some spots are reserved for charging.</td></tr>
<tr><td>Large parking lot near shopping mall, camping site, hotel or airport</td><td>Few visitors park here regularly and chargers here are generally insufficient to enable transition to BEV from ICEV.</td><td>Infrastructure is easy to install with direct access to four parking spaces from a shared corner. Minimal competing land use above and below ground. High turnover site, with a few parking sessions per day per outlet. Uneven utilization throughout the week drives up costs that scale with peak power.</td><td>No significant impact.</td></tr>
<tr><td>Small parking lot in area with industry and offices</td><td rowspan="2">Convenient site that is frequently visited and can potentially replace overnight charging at home. Not a sufficient solution during longer holidays, and reliance on charging at work can make it more difficult to change jobs.</td><td>Indoors installation is easy and an existing grid connection can likely be used. Day-time parking adds to current peak power, unless efficiently load managed. Very low turnover.</td><td rowspan="2">No significant impact.</td></tr>
<tr><td>Large parking lot in area with industry and offices</td><td>Infrastructure is easy to install with direct access to four lots from a shared corner. Little competing infrastructure underground and no competing land use above ground. Low turnover site with one to two medium-length parking sessions per day.</td></tr>
</table>

Energy station, i.e. a dedicated public fast-charger site	Like a fuel station, this site is typically not a destination in itself. Unlike an ICEV, current battery technologies require 20-40 minutes to fully recharge a BEV and we are not aware of any sources that claim this time is likely to decrease below 10-15 minutes within decades. The pause for charging may be a desired break on a long motorway journey, or lost time on the way home from work (including time to get to the site), in which case an opportunity cost is added to the direct cost of charging. Fast charging increases wear on the battery cells, which may shorten their lifespan or lead to reduced vehicle range. Battery packs may not support charging at the greatest power ratings all the way to full charge.	High turnover site that charger operators[11] believe peaks around eight charging sessions per day per charge point, under ideal conditions. Opportunity to provide other services to charging customers, as is common at fuel stations today. Demand is highly sensitive to the availability and pricing of charging at other more convenient locations. Electric fast chargers can be installed anywhere, unlike distribution infrastructure for liquid fuels that is associated with a risk of contaminating spills.	No significant impact. While more charge points are needed than pumps at a fuel station, which increases land use, current fuel stations have wide safety distances that prevent use of nearby land for other purposes.

Table 1. Qualitative comparisons of charger placement at different sites, from the perspective of the charger operator, users and non-users. No type of site is alone sufficient to reach close to full electrification of all the passenger car traffic in the city, and the sites that are most attractive to charger operators are not the same that contribute most to electrification of the fleet.

Charger Placement and Cost of Energy Delivery within Stockholm County

The city of Stockholm desires to know what charging infrastructure is needed to ensure that all passenger car traffic in the inner city can be electric by year 2030. Very little inner-city traffic has both the origin and destination within the inner city, and cars parked nightly in the inner city do not make up a large portion of the day-time inner-city traffic. Therefore, if we are to make all traffic in the inner city electric, we must widen our scope for charging infrastructure to include a larger geographic area.

This analysis therefore looks at the whole of Stockholm County, pictured in Figure 11. The county is the smallest geographic unit for which statistics are available and which with reasonable accuracy can be treated as a closed system, in terms of passenger car traffic.

As discussed in the previous section, cars can be charged at a multitude of possible locations. Locations complement each other, so that vehicles can for instance have access to overnight street charging at home, slow charging at work, fast charging at the nearby shopping mall and fast charging at public energy stations. The more charging infrastructure that is built of one type, the less needs to be built of all other types.

The total amount of energy needed to power Stockholm's future electrified car fleet is unaffected by the selected charging infrastructure solution. The overall goal of the analysis in this section is thus to *identify the cheapest set of infrastructure that is sufficient to deliver this*

[11] Discussion during workshop with Elektrifieringspakten, 30 September 2021. The sites with highest turnover in Oslo were reported to reach around five sessions per charge point per day in 2021.

fixed amount of energy to the population of cars. In addition to minimizing cost, we should strive to find a solution that ensures that no segment of cars are at risk of depleting their batteries, and that all residents have access to charging at similar cost. Some solutions can also be associated with regulatory challenges or high externalized costs, which we want to avoid. All costs are reported in SEK per transferred kWh, to facilitate easy comparison.

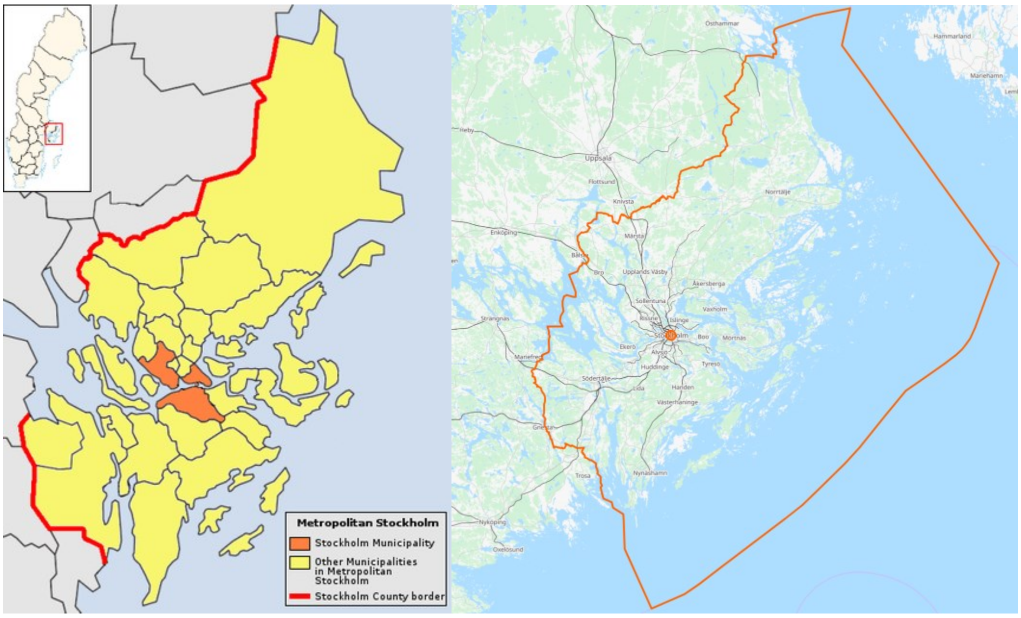


Figure 11. Left: Stockholm County and Municipality, with administrative borders[12]. Right: Road network and settlements around Stockholm[13].

Method and Key Assumptions

Cost modelling of vehicles, earlier in this report, provided us with assumptions of electric vehicles' battery capacity, energy consumption and daily distance. These are used to calculate at what energy level ("state of charge", SoC) each vehicle segment will get access to charging, on average. Acceptability criteria for SoC level on charger access are subjective, but the higher the level, the more convenient and resilient the system becomes and the more likely residents are to buy an electric car rather than one powered by a combustion engine.

Parking within the county is primarily made up of driveways at single family homes, street parking in the inner city, outer city and residential areas, small parking garages in residential buildings and at workplaces, large public parking garages, large lots in residential areas and at work places, and large lots or garages near shopping malls. Many parking spaces are reserved and accessible only to a single vehicle. Some are outside, some are indoors and some are underground. To the best of our knowledge, no single data source exists that can describe where all or most these parking spaces are located. Instead, data resides with 26 municipalities, around 25 major parking operators, and tens of thousands of housing associations, public and private companies. Due to time limitations and that the data is not public, we have also not been able to access survey data capturing mobility patterns within the region[14], in a format sufficiently disaggregated that it can be used to study travel patterns between areas within the city. The data exists and could likely be used in future work to improve the calculations.

[12] Source: Wikipedia, used under Creative Commons license.
[13] Source: OpenStreetMap, © OpenStreetMap contributors.
[14] Resvanor i Sverige2020, Trafikanalys. Source: https://www.trafa.se/kommunikationsvanor/RVU-Sverige/

Rather, parking behaviour within the city and county has been approximated using a simplified model of mobility. This model has ten types of parking (see Table 2), between which vehicles travel. The total population of passenger cars is distributed over the different location types (night-time residency) and we assign a frequency of car use to each group. Regular traffic to work is modelled as an unconditional probability distribution, with each location type receiving cars from all location types proportional to their ratio of night residents. Individual cars always commute to the same location type. Both used and unused cars at a location occupy parking space, but used cars are given priority for charger access. Cars are also used for leisure trips and cars at each location of residency are assigned a frequency with which they visit other location types (Table 3).

The model has many parameters, many of which are uncertain. We have therefore taken significant care to calibrate the inputs such that intermediate values match known point statistics wherever available, such as parking lot occupancy day and night, number of parking spaces of a specific type, distribution of housing types, car ownership per housing type and annual mileage per car. The City's domain knowledge has also been used when setting some parameter values. While deviations from reality may be present in terms of absolute counts, we believe that the resulting electrification and occupancy rates are reliable and remaining differences should only have minor impact on calculated costs per kWh.

Parking spots in the model have capacity for one resident per night (13 hours). During the day (9 hours) they can support one unused car, one commuter car or 3.6 (9/2.5) leisure time visits. Remaining time is assumed to be driving.

Based on these distributions we calculate the number of cars parked at each type of location during night and during day. We assume that the total number of parking spots is the largest of these, plus a small overcapacity margin of around 10%. We also get the number of cars that can charge during night and day, respectively, which is the number of parked cars minus the unused ratio.

It is now possible to assign the percentage of parking spots of each type that are equipped with chargers, which together with parking lot occupancy and ratio of unused cars gives us a probability of accessing a charger at each visit to a location type. By also making use of the previously assigned values of battery capacity and average daily energy consumption, this charger access frequency can be converted to a mean state of charge on charger access.

Now we must make a subjective decision: among all used cars, which cars get priority for charger access? We could assume a first-come first-serve system, but we do not believe this would give an efficient allocation of resources within the population, as cars that arrive later to home or to work than others would have far lower chances of charger access than those with a different schedule. We have instead opted for an assumed efficient booking system, in which all cars take turns to access chargers. An example of a booking system that achieves this outcome is to only allow a single active booking per car, in a regional or city-wide booking system. This booking system assumption is important, and without it, many cars will likely become dependent on public fast chargers.

We must also make a subjective decision regarding the desired state of charge (SoC) level at which cars should access chargers. This too is a matter of resiliency, as unexpected loss of charger access should not lead to a depleted battery. Given that we have assumed a perfect booking system, which may be unrealistically optimistic, we aim for that no residency-commute pair should have an expected frequency of charger access that results in the battery ever going below 60% SoC[15]. Knowing the SoC and battery capacity lets us calculate the amount of energy transferred during each charge session, which together with the duration of parking gives us the average power output from the charger outlet.

Type of parking	Night at (default, percent of fleet)[a]	Night in public garage (of days used)[b]	Unused (percent of group, per day)[c]	Commute to (of all used cars)[d]
Single-family home	31%	0	25%	
Small private garage or lot	17%	0	40%	
Large suburban lot (e.g. Fruängen)	17%	0	30%	
Residential street (e.g. Aspudden)	15%	0	55%	3%
Outer city street (e.g. Sundbyberg)	7%	1/10	55%	5%
Inner city street (e.g. Södermalm)	3%	1/10	55%	2%
City garage, large surface lot	10%		55%	25%
Mall lot				0%
Workplace (small lot)				35%
Workplace (large lot)				30%

Table 2. a) Ratio of the county's fleet of passenger cars that park nightly in each type of location; b) Assumed frequency with which these cars will park in a public parking garage to charge overnight; c) Percent of the cars that are unused on any given day, and thus remain at their overnight location; d) Percent of the (used) cars that travel to and park at each type of location during the day. Commute trips are assumed to result in occupation of one parking spot during the full day.

	Leisure time trips to (every n:th day of car use)				
Type of night parking	Residential street (e.g. Aspudden)	Outer city street (e.g. Sundbyberg)	Inner city street (e.g. Södermalm)	City garage, large surface lot	Mall lot
Single-family home	1/100	1/14	1/50	1/7	1/7
Small private garage or lot	1/100	1/20	1/100	1/14	1/14
Large suburban lot (e.g. Fruängen)	1/100	1/14	1/50	1/7	1/7
Residential street (e.g. Aspudden)	1/100	1/14	1/50	1/14	1/14
Outer city street (e.g. Sundbyberg)	1/100	1/20	1/100	1/7	1/14
Inner city street (e.g. Södermalm)	1/100	1/20	1/100	1/7	1/20
City garage, large surface lot	1/100	1/14	1/100	1/40	1/20

Table 3. Frequency with which cars that are parked overnight in different types of locations are used to make leisure time trips to each other type of location. Leisure time trips are assumed to result in occupation of a parking spot for a shorter duration.

[15] Some car manufacturers currently recommend that the battery is not charged above 80-90% SoC. This would be handled as a car with a smaller battery capacity in our model.

We believe that we have reached a point where the numbers fairly accurately represent the average car mobility patterns within the city, but we also know that there are large local deviations from the norm. For example, we know that some residential areas have full parking occupancy at night, while others classified as the same type have a night-time occupancy of only 20%, but the data we have managed to access does not state which these areas are. Capturing these local variations is left as future work, and could be possible using for instance floating car data from commercial providers, or disaggregated data from official mobility surveys.

Finally, we feed the calculated metrics on charger density and utilization into a charging infrastructure cost model, to calculate resulting cost of energy delivery via chargers installed at each type of location. This gives us a total annualized cost of the charging infrastructure, along with several other quality indicators for a given placement of chargers. The annualization periods used are 20 years for large suburban lots, city garages and mall lots, 15 years for residential street parking and large workplace lots, and 10 years for the remainder.

The cost model for static charging infrastructure assumes that all expensive electronics are centralized and that many cheap outlets share a single expensive charge box and grid connection. This is further handled by setting a number of parking spaces that represent a parking area, for each location type. This concept of an area represents either the size of an average parking garage or lot, or the distance within which residents who park on the street can be forced to walk to their car.

Costs of site and outlet hardware have been provided by ChargeNode, an industry provider, along with assumptions on installation costs and maintenance. Costs of new grid connections, annual grid subscription fees and cable fees to the municipality have been modelled in collaboration with Ellevio, the local electrical grid operator. An overhead of 10% has been added to cover operator related costs. These will collectively be referred to as the *direct* costs of chargers. Non-cable charging interfaces have identical costs for the grid connection and site hardware, but other costs for the individual outlets. Over the lifetime of a site, the choice of charging interface does not make a significant difference in terms of direct cost to the operator.

Charging also results in several *indirect* costs. For chargers using a cable interface and installed on city streets, an opportunity cost of land has been included proportional to the annual license fee per square meter for operating a food truck in the city. Charging interfaces that deliver energy from the road surface rather than via a cable (either inductively or conductively) result in an overhead in terms of additional parts in cars. Energy costs are approximated with the historic average spot prices in the Nordic energy market during daytime and at night, with energy being significantly cheaper during the night (0.3 vs 0.7 SEK/kWh). Finally, the part of today's fuel taxes not tied to emissions has been converted to a cost per km, and then to a cost per kWh. No such tax is applied to electric vehicle charging today. The Swedish VAT rate of 25% is applied when making cost comparisons with combustion engine fuels.

Results

Table 4 presents four scenarios for charger placement within Stockholm county. These scenarios have been manually defined to represent different viable futures, and tuned to minimize total cost and to perform well on the many quality indicators listed in the table. All scenarios make use of the same car movement patterns, described in Table 2 and Table 3.

Scenarios 1-3 include chargers along city streets, which are kept few by requiring nightly street-parked cars to spend one night every two weeks in a public parking garage. Scenario 4 includes no on-street charging, with the consequence that the same cars must charge one night every week in a public garage. Enabling this behaviour may require changes to the rules governing night-time use of public parking garages. While this behaviour is not strictly necessary to make the first three scenarios work, it does improve resiliency for street parked cars, reduces the required number of on-street chargers, and democratizes access to cheaper charging in garages. The behaviour is necessary in scenario 4.

An alternative real-world interpretation of the model assumption of occasional parking in public garages is to not install any on-street charging near garages and to instead place on-street charging sites interspaced between garages. In this case, residents who normally park on the street and live near a garage would reserve garage space on those nights when the car needs to be charged, while those living further from garages would always charge on the street.

All four scenarios have been defined such that no cars need to be dependent on public fast charging at energy stations. While it is possible that fast charging will be responsible for delivering much of the energy to the fleet of cars, this is not a future we see as desirable. First, the cost of fast charging today is around 3-6 SEK/kWh (and only VAT is applied). Second, charging at energy stations imposes an indirect cost on users in terms of an opportunity cost of time. While this cost differs between users, we assume the average to be at least 50 SEK/h for a car owner. If charging takes 15 minutes and adds 50 kWh to the battery (rather generous assumptions) and getting to the energy station only takes an additional five minutes, the opportunity cost of time adds another 0.33 SEK/kWh. With a smaller battery (e.g. in a PHEV), the opportunity cost could easily surpass 1 SEK/kWh. Fast charging also reduces the lifetime of the battery pack, through increased wear. Combining all of these, non-destination fast charging ends up with an approximate total cost of 5-8 SEK/kWh, i.e. at least twice the end-user cost of static charging in the proposed scenarios.

All four scenarios include chargers installed at 50% of single family home parking places. This represents a simplification where all single family homes have one installed charger, but space for two parked cars.

Among the four scenarios, scenario 1 is superior in almost every regard:

1. all vehicles have regular access to night-time charging;
2. lowest total system cost (though the relative difference after taxes is small);
3. lowest average and lowest maximum user cost of charging;
4. lowest total daytime power demand;
5. a high average SoC level on charger access for all residence-commute pairs;
6. a low variance in charger accessibility between travel patterns;
7. little static charging infrastructure along city streets.

Although it is preferable from an electric grid perspective to allocate as much charging as possible to the night, it is possible that there are limits to electricity supply during night. This is elaborated on in Pros and Cons of Dynamic vs. Static Charging on page 45.

The remaining three scenarios have been included for reference. Scenario 1 is the result of manual tuning to perform well on as many of the quality indicators as possible. Scenario 2 is identical to scenario 1, plus the addition of more public static charging closer to the city centre, primarily on city street lots. As sufficient charging was already provided in scenario 1, this adds cost without providing any real benefits. If charging infrastructure is paid for by those who use it, this doubles the infrastructure cost of charging for inner city residents. Easier access to chargers in day-time also transfers energy demand from night-time to daytime, unless city residents begin to avoid these chargers due to their high cost. As around half[16] of the public parking spaces in the inner city are occupied by unused cars on an average day,

[16] As estimated in Table 2.

installing chargers at more than 40-45% of parking spots provides no benefit at all, as long as incentives are in place to discourage multi-day parking that blocks charger access.

Scenario 3 exemplifies a conceptually simple future where chargers are distributed throughout society. This may be a likely scenario if regulatory issues and local surface or subsurface conditions effectively prevent installation of chargers in many locations. Costs are around 10% greater than in scenario 1, and total day-time power demand from the electricity grid doubles. Modifying this scenario by installing more chargers at any type of location, without removing them elsewhere, will raise overall costs.

Scenario 4 represents a desire to completely avoid static charging on streets in and near the city centre. This results in a shortage of night-time charging for residents who depend on street parking and who commute to locations that also lack charging options. Consequentially, the cars are forced to park and charge with greater frequency overnight in public parking garages. Otherwise, these cars must depend either on (more costly) public fast charging at energy stations, or spontaneous charging at locations visited during leisure time (city garages and shopping malls), which will be insufficient for many cars with this pattern of use. Adding chargers in the rows labelled “workplace” will not improve the situation, as these rows represent locations that are never visited by the cars for which charging is least available. Peak daytime power from the grid is comparable to that in scenario 3, and twice that of scenario 1.

Itemized costs for charging at each type of location in scenario 1 are shown in Figure 12. All infrastructure costs are low due to the very high utilization of installed charging capacity achieved in the scenario. Electricity adds up to twice the cost of infrastructure and the mean cost of electricity is approximately double for placements that predominantly lead to daytime charging compared to night time charging. Taxes alone (transferred from today’s combustion engine fuels and not applied to EVs today) are 1-2 times the costs of infrastructure and energy together. Though today’s non-emissions-related taxes may never be applied in this particular way to EV charging, it seems reasonable that the same tax revenue will continue to be collected somehow and it has been included in the model to facilitate easier comparison of BEV and ICEV economy. Energy tax that is applied to electricity today has not been included, as this would imply a change (reduction) in taxation.

Static on-street charging in both Figure 12 and the remaining scenarios in Table 4 and have been modelled to use non-cable interfaces that transmit energy from the parking surface. The figure therefore includes the cost of the additional charging interface in each car that uses the on-street chargers. If cable interfaces are used, the cost labelled “car components” in Figure 12 will be replaced by an opportunity cost of land with very similar magnitude, and total system cost would remain unchanged. Using cable-based interfaces for static on-street charging in scenario 2 would result in an opportunity costs of land more than twice the “car component” cost, as more parking spaces are equipped with chargers in this scenario.

Additional information on scenario 1 is listed in Table 5 and Table 6, including the number of sites at each location type, the number of outlets per site and itemized costs. Multiplying these numbers with the costs in Figure 12 and the annual delivered energy, we get the total annualized cost of energy delivery for Stockholm County, shown in Figure 13.

Scenario	Ratio of parking lots with chargers: 1. Recom-mended	2. More street charging	3. Evenly distributed	4. Minimal street charging
Single-family home	50%	50%	50%	50%
Small private garage or lot	40%	40%	30%	25%
Large suburban lot (e.g. Fruängen)	40%	40%	30%	25%
Residential street (e.g. Aspudden)	15%	25%	10%	15%
Outer city street (e.g. Sundbyberg)	10%	25%	10%	0%
Inner city street (e.g. Södermalm)	10%	50%	10%	0%
City garage, large surface lot	10%	20%	10%	40%
Mall lot	0%	0%	10%	40%
Workplace (small lot)	0%	0%	10%	0%
Workplace (large lot)	0%	0%	10%	0%
City garage visit fq. (of days used)	1/10	1/10	1/10	1/4
Total CAPEX (MSEK)	8 546	10 025	10 490	8 943
Total levelized cost (MSEK/year)	3 317	3 824	3 773	3 532
% daytime energy	15%	24%	28%	29%
Total kW nighttime	642 553	575 409	546 105	531 729
Total kW daytime	171 078	259 088	336 000	341 654
Cars dependent on fast charging	0%	0%	0%	0%
Weak OD pairs (resiliency)	0	0	0	0
Mean SoC on access (resiliency)	76%	84%	75%	77%
StdDev SoC on access (low is fair)	8%	9%	10%	10%
Lowest avg. SoC on access (resiliency) for	Single-family home	Small private garage or lot	Small private garage or lot	Small private garage or lot
Highest cost of charging at	Inner city street (e.g. Södermalm)	Inner city street (e.g. Södermalm)	Workplace (large lot)	Residential street (e.g. Aspudden)
Mean SEK/kWh (infra + energy)	0.8	1.0	1.0	0.9
Max SEK/kWh (low vs. mean is fair)	1.5	2.0	1.7	1.4
Eqv. mean SEK/liter, incl. taxes	10.0	10.8	10.7	10.4
Eqv. max SEK/liter, incl. taxes	13.8	16.7	14.9	13.1

Table 4. Comparison of four scenarios of deployed static charging infrastructure in Stockholm County. All four scenarios include sufficient charging infrastructure that no cars should be dependent on (more costly) public fast charging. The best value on each row is highlighted in grey. Charging costs in SEK/kWh include direct and indirect costs of charging, but not taxes. The bottom two rows show the fuel price at the pump that would result in equivalent fuel economy for a combustion engine car, taking into account fuel consumption and after transferring today's non-emissions related fuel taxes and applying VAT.

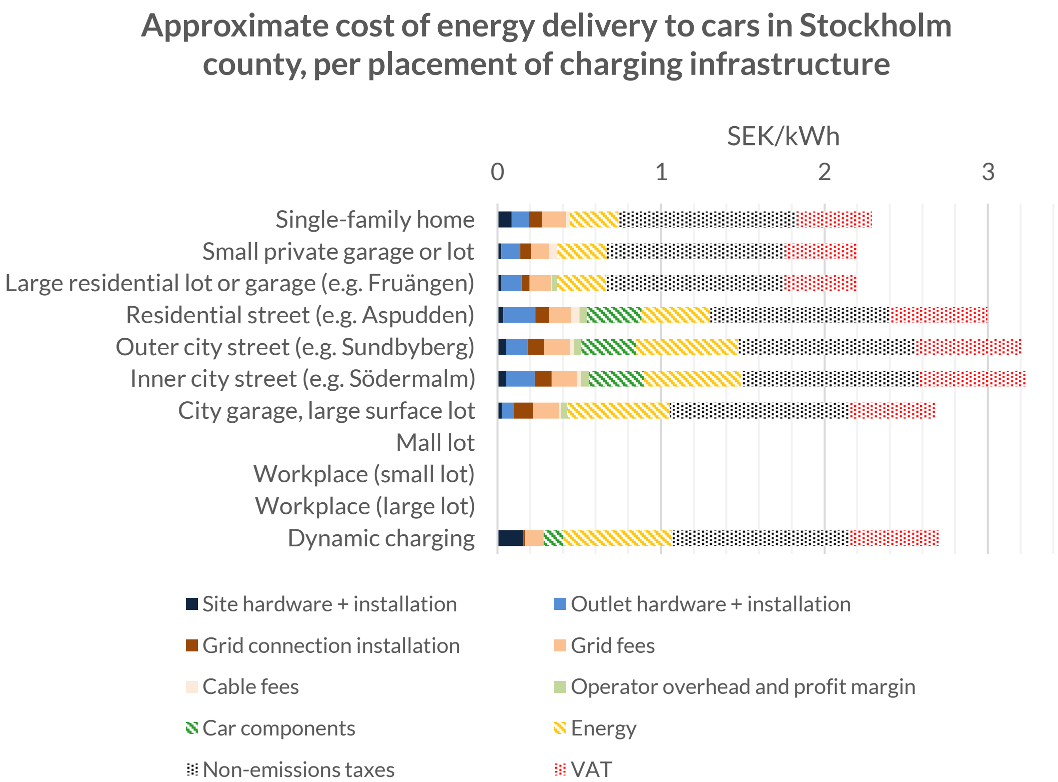


Figure 12. Estimates of the total cost of energy delivery via static charging placed as outlined scenario 1 in Table 4, plus dynamic charging (using default parameter assumptions). Solid coloured bars represent direct costs, dashed bars represent indirect costs and dotted bars are taxes. Note that the cost axis is per unit of delivered electricity, which penalizes infrastructure placements that result in low average occupancy rates, uneven power loads, or low energy per charge session. Energy costs vary by time of day and placements that result in more night-time charging have lower energy costs. Sites also have different annualization periods, described in the methods section on page 26. A difference in pricing of one SEK per kWh is approximately equivalent to a difference of 3.5 SEK/litre for petrol and diesel.

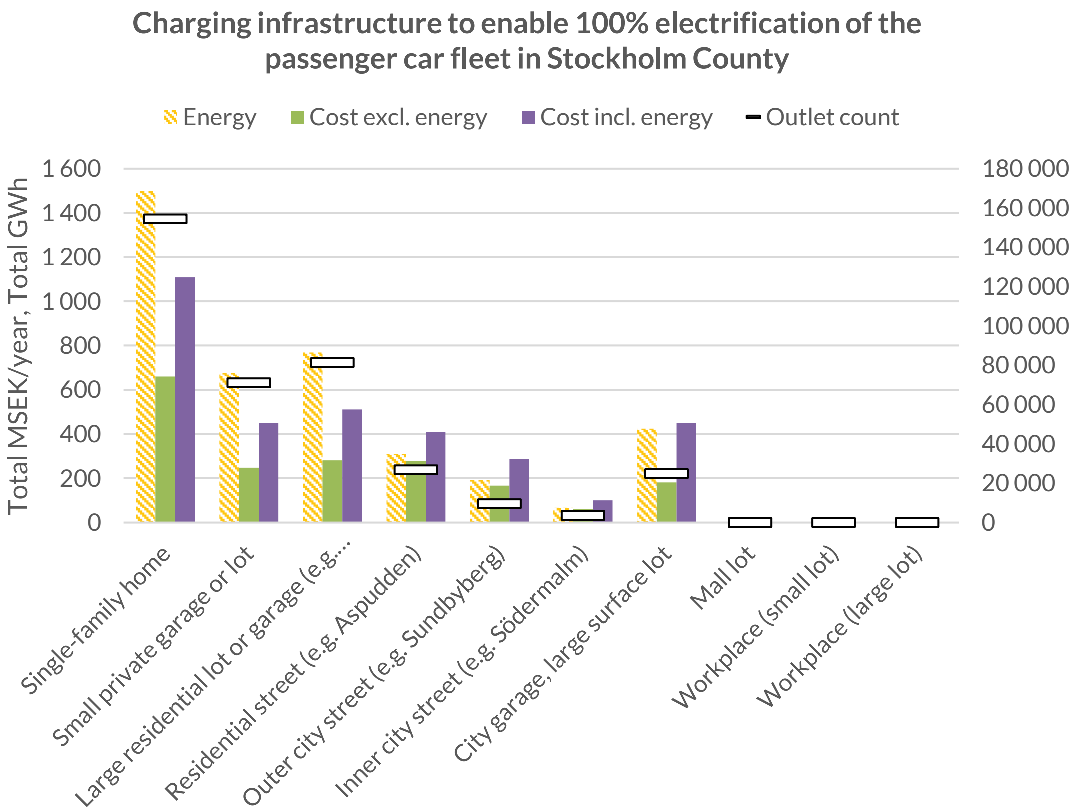


Figure 13. Summary of annualized total cost (excluding taxes), number of outlets and total energy delivered per site type, corresponding to scenario 1 in Table 4. Values are for 100% electrification of the passenger car fleet.

							Parking spot occupancy		Charger occupancy		Peak power per site (kW)	
	Number of parking spots	Ratio of parking with charging	Parking spots per grid connection	Number of sites/grid connections	Number of outlets	Outlets per site	Night	Day	Night	Day	Night	Day
Single-family home	309 225	50%	2	154 613	154 613	1	100%	25%	100%	0%	4	4
Small private garage or lot	178 054	40%	10	17 805	71 222	4	95%	38%	100%	0%	9	4
Large suburban lot (e.g. Fruängen)	203 490	40%	200	1 017	81 396	80	83%	25%	100%	0%	149	22
Residential street (e.g. Aspudden)	179 550	15%	200	898	26 933	30	83%	57%	100%	74%	56	44
Outer city street (e.g. Sundbyberg)	96 117	10%	200	481	9 612	20	69%	83%	100%	100%	36	106
Inner city street (e.g. Södermalm)	36 227	10%	200	181	3 623	20	79%	87%	100%	100%	39	93
Large public garage or lot	249 251	10%	300	831	24 925	30	42%	91%	100%	100%	36	119

Table 5. Summary of assumed parking capacity for each location type in Stockholm County, along with charger capacity corresponding to scenario 1 in Table 4. Charger occupancy is high as a result of an efficient booking system and that relatively few parking spots are equipped with chargers. Daytime charger occupancy in residential areas is non-zero as a result of an observation from the city that people living outside of the city sometimes park here during the day to then switch to public transport to get into the city, but great variations likely exist between neighbourhoods.

		Single-family home	Small private garage or lot	Large residential lot or garage (e.g. Fruängen)	Residential street (e.g. Aspudden)	Outer city street (e.g. Sundbyberg)	Inner city street (e.g. Södermalm)	City garage, large surface lot
Parking spaces per site	count	2	10	200	200	200	200	300
Outlets per site	count	1	4	80	30	20	20	30
Site peak power	kW	3.7	9	149	56	106	93	119
Peak power per outlet	kW	3.7	3.7	22.0	22.0	22.0	22.0	22.0
Avg. energy price	SEK/kWh	0.3	0.3	0.3	0.4	0.6	0.6	0.6
Outlet hardware + installation	SEK/site	7 400	29 600	680 000	660 000	440 000	540 000	255 000
Site hardware + installation	SEK/site	7 500	7 500	229 032	117 560	176 928	161 668	192 398
Grid connection installation	SEK/site	6 700	21 244	549 193	281 300	330 773	318 057	868 665
Total CAPEX	SEK/site	21 600	58 344	1 458 225	1 058 859	947 700	1 019 725	1 316 062
Maintenance	SEK/year	200	800	38 400	0	0	0	14 400
Grid fees	SEK/year	1 300	3 539	75 014	30 345	53 444	47 535	59 536
Opportunity cost of land	SEK/year	0	0	0	3 650	4 563	7 300	0
Levelized total cost per site, excl. energy	SEK/year	3 835	11 924	206 708	200 859	286 822	282 585	157 212

Table 6. Summary of site configurations and costs for static charging infrastructure in scenario 1.

A few perhaps unintuitive pitfalls have emerged from the modelling work. First, the importance of an efficient booking system for chargers cannot be stressed enough. A fair booking system is the single most efficient way to distribute access to chargers within the population of cars, which then enables us to greatly reduce the number of chargers without risking that any vehicles run out of charge. Without a good booking system, charger access becomes random in theory. Random access means that for a ratio *r* of chargers per number of parking spaces cars have a probability of $(1-r)^n$ of going completely without charging for n days. If a third of cars can charge every night and access is random, 8% of cars will go seven days or more without charger access. With a good booking system, all cars would have access every third day. In practice, random access likely means that charging will be unavailable to those residents who return later than others from work.

Second, it is *not* safe to assume that a slow charger used nightly will be more economical if it is also used for faster charging in daytime. While the energy delivered per day increases, any increase in the peak power of the site also raises costs. If the new peak power is utilized only for a short time of the day, overall utilization decreases by supporting fast(er) charging. It *is* safe to assume that sites that are underutilized have some spare capacity for more rapid charging of fewer vehicles, while during full occupancy, the available power per vehicle is reduced. Sites used in the model are equipped with outlets supporting 22 kW, but the capacity of the grid connection for each site is set based on the average power per outlet (max of day and night).

Third, the opportunity costs of land in the city centre are very high, and may still be underestimated in the model according to discussions with the city as well as with city planning researchers within RISE. Land use, and the associated opportunity cost, can be eliminated by switching to a charging interface that provides power from the parking surface rather than through a cable. These are the same charging interfaces that are used for dynamic charging on so-called electric roads. The lifetime cost per outlet does not differ significantly with these interfaces, but there is an overhead in the form of additional parts required in vehicles. The total cost of these parts is less than the (assumed) opportunity cost of land when more than 10% of parking spaces are equipped with chargers. The cost of these parts has been set in the model to 7000 SEK/car with a lifetime of 15 years, based on data from manufacturers provided in prior research projects. If the cost per energy of the charging interface in the car would decrease[17] or if the opportunity cost of land use is greater than assumed, then the system cost would be reduced by using road-based charging interfaces for on-street parking, instead of cable-based interfaces. Using different charging interfaces at different locations throughout the city would be undesirable, but in this case a subset of street chargers could be equipped with both charging interfaces, to ensure that chargers can be used also by visitors during the day.

Fourth, for a charger placement scenario to be viable and cost efficient, it should include charging either at all night-time location types or all daytime location types. If not, there will likely exist vehicles that have no access neither at home nor at work. Installing chargers at all night-time and all daytime locations is unnecessarily costly, unless the density at each is very low.

Static Charging within Stockholm Municipality and the Inner City

The original question for this assignment was determining how much public charging should be installed on public land (i.e. on-street parking) in the administrative region of Stockholm Municipality. We are now able to answer this question.

Table 7 lists the number of street parking spots per district within Stockholm Municipality. The districts have been classified according to their location type and the recommended number of sites and outlets have been listed in accordance with infrastructure placement in scenario 1 from the previous section. The table also includes investment cost per district as well as levelized (annualized) cost including maintenance, operations and opportunity cost of land. The number of sites and outlets in the table, as well as resulting costs, are approximate. Parking occupancy rates are known to differ among and within the residential street parking districts, but per-district occupancy data was not available. Collecting and incorporating such data is recommended before detailed planning of any build-out. The table row “other areas without fees” is labelled such due to a lack of access to disaggregated data on the number of on-street parking spaces in district without parking fees.

Investment cost grows by approximately 20% if chargers are grouped into twice as many sites with half as many outlets per site. A 20% increase in CAPEX results in a much smaller relative increase in total levelized cost of charging, in particular if opportunity costs of land and taxes are included. An indirect benefit of grouping chargers into sites is that fewer locations must be searched to find an available charger, though a booking system completely eliminates such search traffic.

[17] Cost per kWh would decrease if technology development and mass production would reduce the cost of parts, or if street-parked cars on average have greater energy consumption than assumed. A representative of one electric road technology company claimed in private communication that 2000 SEK/car is not unreasonable to expect in the future. A representative of a competitor stated that 10000 SEK is already a level that assumes mass production, while a third stated that 10000 SEK is too high but would not provide a lower number.

Based on the anticipated rate of EV sales (Figure 8), it is strongly recommended that the these sites are built out as quickly as possible. The reduction in investment cost from installing entire sites at once likely far surpasses any operational savings from a gradual rollout.

		On-street parking spots[18]	Number of outlets	Number of sites	CAPEX	Levelized cost, excl. energy
Inner city street parking	City	1 400	140	7	7 138 074	1 978 094
	Gamla Stan	200	20	1.0	1 019 725	282 585
	Kungsholmen	7 400	740	37	37 729 819	10 455 640
	Stora Essingen	750	75	3.8	3 823 968	1 059 693
	Södermalm	10 500	1 050	53	53 535 554	14 835 705
	Vasastaden	6 000	600	30	30 591 745	8 477 546
	Östermalm	11 300	1 130	57	57 614 453	15 966 044
Residential street parking	Bagarmossen	2 400	360	12	12 706 313	2 410 304
	Bromma	3 627	544	18	19 200 651	3 642 237
	Ekhagen	200	30	1.0	1 058 859	200 859
	Enskede	4 300	645	22	22 765 478	4 318 461
	Hammarbyhöjden	6 000	900	30	31 765 783	6 025 760
	Hägersten	5 800	870	29	30 706 924	5 824 901
	Midsommarkransen	4 100	615	21	21 706 619	4 117 603
	Riksby	2 400	360	12	12 706 313	2 410 304
	Traneberg	1 850	278	9	9 794 450	1 857 943
	Årsta	3 683	553	18	19 500 661	3 699 147
	Other areas without fees	27 000	4 050	135	142 946 025	27 115 919
	Total	98 910	12 959	360	373 365 390	87 562 824

Table 7. Estimated number of on-street static charge points to install to enable electrification of cars that depend on street-parking today, per district and in total for Stockholm Municipality. Chargers in the inner city are on every 10th parking space, grouped in sites of 20 outlets with a shared grid connection, while 15% of parking spaces in residential areas have chargers, grouped into sites of 30 outlets. Data on number of parking spaces per area were only available for residential areas with paid parking, hence the grouping of other areas into one row. The same charger-to-parking ratio has been used for all residential districts, but in reality, parking occupancy is known to vary greatly between and within districts[19], which means that the number of sites/chargers should be adjusted up or down based on local need. CAPEX (capital expense, SEK) includes site and outlet hardware, installation and grid connection. Levelized cost (SEK/year) includes CAPEX, maintenance, grid fees, cable fees, operational overhead and opportunity costs of land, evenly distributed over the expected lifetime of the site. Highlighted table cells contain values that were missing in the provided data and which have been approximated based on other available data on issued parking permits.

[18] Data on parking space and permit counts were provided by Trafikkontoret, Stockholm Stad.
[19] Source: Parkeringsundersökning taxa 4, Nyttjandegradsundersökning natt våren 2018, which observed street parking occupancy rates around apartment buildings from less than 20% to more than 95%, with a mean around 80%. Assumptions used in the model were residential parking occupancy rates of 83% at

Sensitivity Analysis

This section elaborates on the effects of changing different model assumptions related to static charging.

Intraday energy price volatility: The spot price of energy fluctuates with time of day. As of 2021, the energy price in Stockholm is higher during the day than at night, with values of 0.7 (day) and 0.3 (night) SEK/kWh used in the model. Our understanding is that the cost difference is caused by that methods of energy production with greater cost per kWh (e.g. garbage combustion) are used to raise power output during peak load, beyond what can be regulated with cheaper sources (e.g. hydro, nuclear and wind).

An increasing ratio of solar power in the energy mix[20] will add a cheap energy source with output only in day-time. This brings the supply curve closer to the demand curve, which should decrease the intraday price differences of energy. Furthermore, both solar and wind power are intermittent in their production. With both intermittency and rapidly declining costs of batteries, it seems safe to assume that some capacity of energy storage will be installed in the grid to stabilize supply and demand, whether that is through dedicated storage or vehicle-2-grid (V2G) technology. Energy storage should also contribute to lower intraday variations in energy price. Meanwhile, the relative demand of energy during night and day could change with the increasing electrification of society, of which vehicle charging makes up a non-negligible part. With changes possible to the relative levels of both supply and demand during different times of day, future energy prices are difficult to predict.

Intraday grid fee volatility: Fees to the grid operator make up a substantial part of the total cost of energy delivery to electric vehicles. This fee covers upgrades and maintenance to the grid as a whole, that are not tied to any individual customer. Ellevio claims that charging of the city's vehicles will incur a much smaller need for upgrades to the grid if the charging takes place at night than during day. However, this is not reflected in today's grid fee structure. Grid installation costs and fees are today only influenced by peak load (kW) during a longer time period, not by when this peak load occurs. Assuming that the sum of all collected grid fees must remain unchanged, and that most energy is consumed in day-time, time-of-day-varying grid fees could reduce the cost of charging at night, while having little effect on the cost of day-time charging.

Site scale: Levelized cost of energy delivery is strongly affected by the scale of the site. Grid-related costs are proportionally much greater for small sites (low total energy transfer per day) and installation of small sites will only be economically viable immediately next to a grid access point or at locations where an existing grid connection can be used. For very large sites (e.g. large mall lots), grid installation costs are negligible, regardless of distance to the grid connection point. For a given site, increasing the number of hours per day that the infrastructure is in use (at peak site power) will always reduce cost per delivered energy. As a rule of thumb, the cost of energy delivery (excluding energy) can be assumed to be approximately five times as high for sites with a single outlet as sites with 100 outlets, all else kept equal.

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night and 57% during the day, with 55% of residents' cars left unused over the day. Unused cars are not assumed to occupy chargers, leading to an assumed charger utilization rate of 100% at night and 74% during the day when 15% of parking spaces are equipped with chargers.

[20] Solar power does not have as much potential as wind power at Nordic latitudes, but electricity is increasingly traded in an interconnected European grid and solar power is expected to make up a substantial part of future electricity production further south.

Infrastructure utilization rate: There are several interlinked model parameters that affect the overall utilization rate of the built charging infrastructure, which in turn affects its cost per delivered energy. These are the degree of colocation of charging points into sites, energy delivered per charge session, charging sessions per outlet per day, annual driven distance per vehicle, and energy consumption per vehicle km. Indirectly, energy per charge session is affected by placement and pricing of other charging infrastructure. To explain, we look at a parking garage, in which the same set of cars park every night. The vehicles are used for commuting to work and they charge exclusively in the garage. Charge points are installed for less than the total number of spaces and vehicles must take turns using the charge points. A desire for greater convenience may motivate an increase in the number of charge points in the garage. This will increase the cost of the charging infrastructure, but will not affect the total energy used by the vehicles over time and thus has no impact on grid related costs.

Land use on city streets comes with a high opportunity cost and many European cities actively try to remove street parking altogether wherever possible. The cost of land use makes inefficiently utilized charging infrastructure along city streets (with cable interfaces) prohibitively expensive.

Incentives that increase turnover on public chargers can shorten the time in which the same energy is delivered, increasing the total energy delivered from the site. This can but does not always result in lower cost per delivered kWh. While energy sold will increase, so will the sites' peak power, which results in increased (particularly grid-related) costs.

Order of charger deployment: Access to some form of charging is a prerequisite to get an electric car, but not all cars will be replaced simultaneously. Recently purchased ICEVs will likely be retained for at least a couple of years, and current owners of second, third or fourth hand cars are unlikely to buy a brand new EV as their next vehicle, thus must instead wait for EVs to become available in the used car market. In other words, the need for charging infrastructure grows with the gradual electrification of the fleet.

However, it is unclear in what order to install chargers. Most likely it is most cost effective to fully build out all charge points at a site when the site is installed, though grid contracts can be adjusted with growing demand as needed. Ordering sites is much less straightforward. Vehicle purchases (of new and used cars) should be relatively evenly distributed across the city and some infrastructure must therefore be installed everywhere to affect these decisions. At the same time, EV ownership is and will remain greater in more affluent areas of the city, suggesting that these areas need more chargers. On the other hand, we have seen that electrification is (or will soon) be highly cost saving, implying that less affluent areas are those most in need of a transition. Further analysis is likely needed to better understand the social implications of different deployment strategies.

Dynamic Charging Infrastructure

Technologies

An electric road system (ERS) enables transfer of electric power from a road to a moving vehicle for both propulsion and charging of battery. ERS technologies are rapidly maturing and are being evaluated in several countries at test facilities and pilot installations on public roads. There is so far no large-scale deployed and widely-used electric road in the world.

Currently, there are three main concepts for road electrification: overhead conductive lines, conductive rails in a road surface, or inductive wireless solutions. All these concepts have their advantages and disadvantages and are being developed and marketed by different actors.

An overhead line solution uses conductive wire lines (also known as catenaries) above the vehicle to provide the energy. The energy is transferred to the vehicle by means of a power receiver device (sometimes called a pantograph) installed on top of the vehicle, and which follows and detaches automatically from the overhead lines. This technology is marketed by Siemens and does not support passenger cars, but heavy trucks and buses can be charged at approximately 200-800 kW.

A rail solution for conductive energy transfer from the roadway to electric vehicles uses conductive rails installed in or on the road to provide the needed energy. The energy is transferred to the vehicle via a power receiver pick-up arm installed beneath the vehicle, and which follows and detaches automatically from the rail. Several companies market solutions, including Alstom, Elonroad, EVIAS and Honda. Rail solutions support all types of vehicles, with charging power for light vehicles around 25-50 kW and heavy vehicles around 150-400 kW.

A wireless solution uses a magnetic field to provide the energy. Electric current in primary coils installed in the roadway create magnetic fields which induces current in a secondary coil installed beneath the vehicle. Providers include OLEV, Bombardier, WAVE and Electreon. Charging power per vehicle is approximately 3.6-20 kW for passenger cars and up to 100 kW for heavy trucks.

We do not recommend that the city selects a technology capable of providing less than 20 kW to passenger cars for dynamic charging. All technologies except overhead lines can be considered for static charging.

Method and Key Assumptions

It is beyond the scope of this report to thoroughly investigate whether dynamic charging using electric road systems (ERS) would provide a more cost efficient solution than static charging for powering a future electric vehicle fleet in Stockholm County. Rather, we provide an analysis of what the cost of energy delivery from ERS would be under several possible scenarios.

The cost of road infrastructure is estimated at 12 MSEK/km, plus 1500 SEK/kW-km (i.e., the road costs a little more when it needs to support heavy traffic than when only a few vehicles drive on it). There is an additional cost of a connection to the electricity grid approximately every 20 km, along with an annual grid subscription fee. Grid related costs are determined using the same method as that used for static charging. Road and grid costs are annualized over 30 years.

16 years ago, in 2005, Stockholm County had a total of 909 km of motorways (Europa- and riksvägar), 2,707 km of regional roads (länsvägar) and 17,426 km of other roads, for a total of 21,041 km[21]. The road network is assumed to be of similar length today. We do not know how many road km that would need to be electrified to power a given percentage of the county's car fleet, but we do know that the traffic is very unevenly distributed in the network.

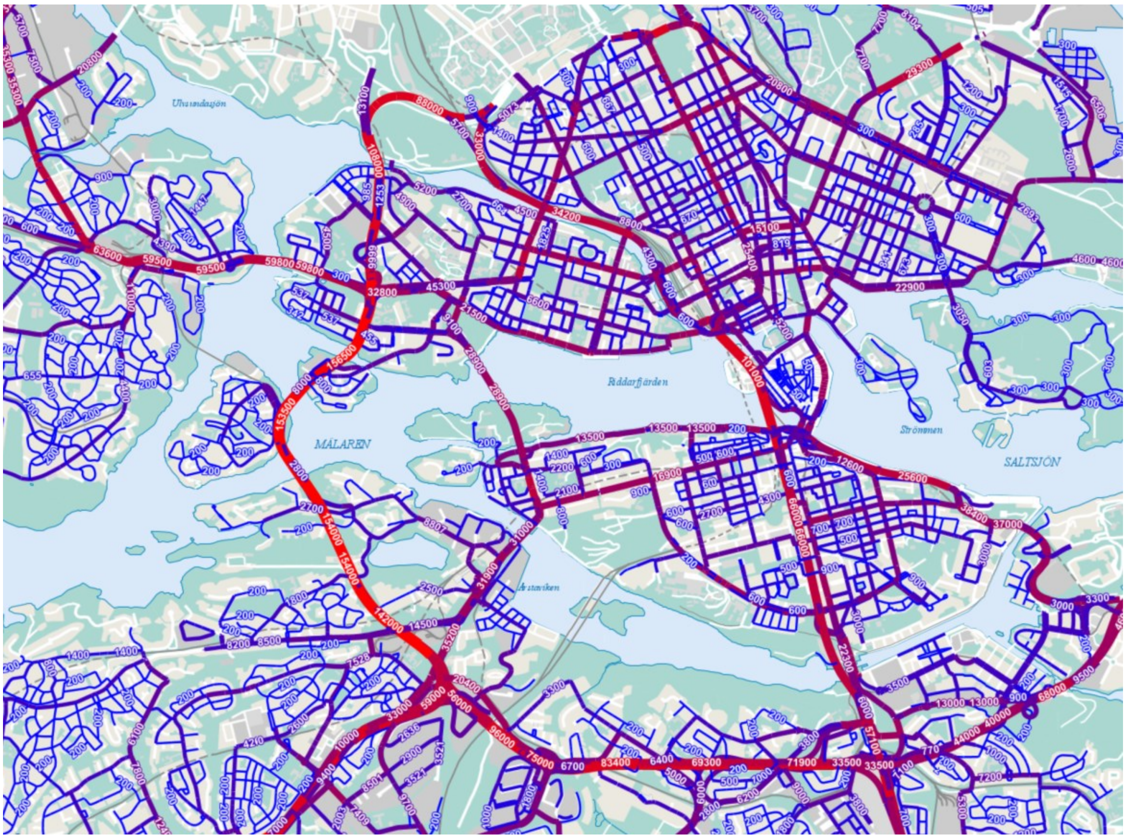

Figure 14. Total (light and heavy) annual average daily traffic (AADT) on roads in central Stockholm[22].

The assumptions around which sensitivity analysis will be performed is an ERS installation of 1000 km, supporting 70% of the county's passenger car fleet, with a mean speed of 50 km/h, a mean bidirectional annual average daily traffic (AADT) of 14300 and 40 kW per vehicle from the road. Figure 14 gives an indication of what roads have AADT values above or below this number. Power per vehicle and mean AADT are inferred from the road distance, total fleet km and maximum AADT under assumption that road use is exponentially distributed, but average speed and number of cars using the electric road are guesses. Each car using the electric road is equipped with a charging interface at a cost of 7000 SEK with an annualization period of 15 years.

Passenger cars use approximately 20 kW at 70 km/h and 30 kW at 110 km/h, based on a simplified assumption of a constant energy consumption of 0.28 kWh/km. If the road provides less than this power, cars needs to draw supplementary power from their batteries but get extended range from the road. If the road can provide more, the surplus is used for charging.

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[21] Source: Statistics Sweden (SCB), Väglängder och vägbredder enligt NVDB per län 2005, https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/markanvandning/transportinfrastrukturens-markanvandning/pong/tabell-och-diagram/vaglangder-och-vagbredder-enligt-nvdb/vaglangder-och-vagbredder-enligt-nvdb-per-lan-2005/

[22] https://miljobarometern.stockholm.se/trafik/motorfordon/trafikfloden-i-stockholm/

Traffic is also unevenly spread over the day. Lacking data from the road network in question, we generated a distribution, shown in Figure 15, of assumed traffic throughout the day. This distribution is used to determine the peak power per grid connection (≈ 15 MW) and the ratio of all electricity that is bought at daytime prices (≈ 90%). The average spot price of electricity is set to 0.5 SEK/kWh, which is lowered by 40% to 0.3 SEK/kWh during night and increased by the same amount to 0.7 SEK/kWh during day. These are the same electricity prices as those used in the calculations for static charging.

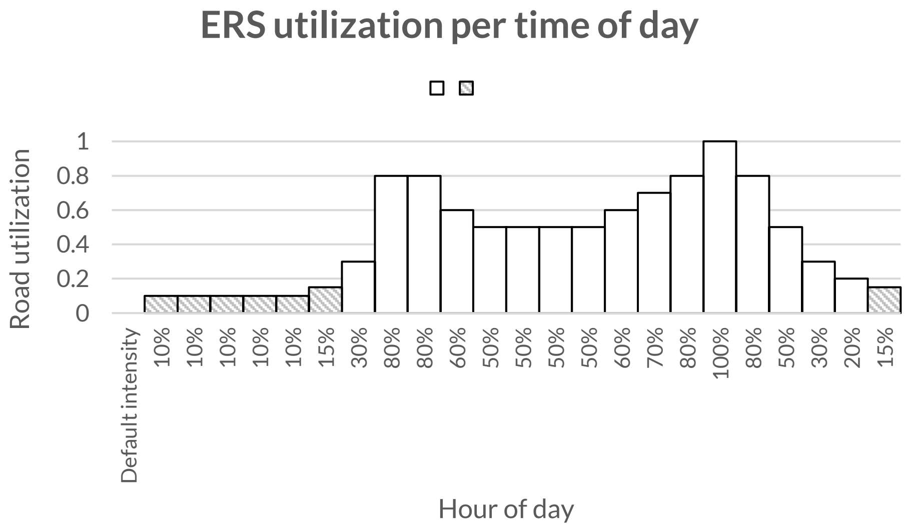

Figure 15. Estimated ERS utilization per time of day, with 90% of road use taking place during daytime. The price of electricity is significantly higher during the day than during the night, resulting in high energy costs for a dynamic charging solution.

Dynamic Charging for Stockholm's Fleet of Passenger Cars

As long as a vehicle receives more power from the road than it uses for propulsion and auxiliary functions, the battery charge will increase while driving on the electric road. Ideally, this means that vehicles can charge on electrified and densely trafficked main roads and simultaneously gain sufficient additional range for driving on more peripheral roads. For example, roads coloured red in Figure 14 could be electrified to enable cars to traverse roads coloured blue on battery power. Table 8 and Table 9 show how the speed of the vehicle and the power from the road affect this range gain. Vehicle energy consumption in kWh/km is assumed to be unaffected by speed in these tables.

Total cost of energy delivery using dynamic charging with the assumed parameter values is very similar to the previously calculated total cost of static charging. The difference should not be considered significant, given the many assumptions and approximations used in the calculations.

A sensitivity analysis of total cost of dynamic charging is given in Table 10 and Table 11. Default parameter values are shown in bold. Energy costs are greater in day-time than at night, resulting in high energy costs in the default case. Table 10 shows how if this cost difference decreases in the future, or if more traffic is shifted to night-time, dynamic charging becomes more cost competitive vs. static charging. However, the impact on total cost of charging is small. Table 11 shows how the total cost of energy delivery is affected by the size of the ERS network, vs. the ratio of the car fleet that relies on dynamic charging. 200 km of ERS will be cost competitive if it supports at least 10% of the fleet, and up to 1000 km of ERS will be cost competitive if it supports at least 50% of the fleet. Total CAPEX for 1000 km of electric road is approximately 14 billion SEK and annualized over 30 years.

It remains to be studied how an ERS network would interact with static charging solutions, and different ERS placements would likely have different impact on the cost of charging as well as demand for chargers installed at the different location types that were compared. It also remains to be studied how static and dynamic charging could best complement each other. Given that traffic densities are greatest on roads closer to the city centre, we speculate that dynamic charging would primarily be a replacement for (all types of) static charging installed in the most densely populated areas.

The additional cost per kWh in the vehicle of adding a secondary charging interface is high for inner city vehicles, which have very low annual energy consumption. Pick-up cost per kWh is much lower for rurally based vehicles that both drive further and have a greater energy consumption per km, assuming ERS is in place to deliver that energy. The charging interfaces used for dynamic charging are the same as those proposed to minimize the opportunity cost of land use for static chargers installed at on-street parking spaces, but the vehicles that use on-street parking are also those with lowest annual energy consumption.

Finally, to get an indication of where ERS would be best placed, we turn to Figure 16. The map shows roads within Stockholm Municipality, with line thickness proportional to total time spent there by vehicles (i.e. potential for high energy transfer). Heavy vehicles have been assigned greater weight than light vehicles, as they have approximately 4-5 times greater energy consumption and can receive greater power from the road. According to this data, the best locations for dynamic charging infrastructure appear to be motorways, frequently congested inner-city streets and streets with low speed limits but relatively high traffic flows. It is not possible from this map to estimate to what extent placement at different locations would affect demand for static charging infrastructure installed in different locations.

We have not been able to access any equivalent data for the county as a whole. Prior work has to our knowledge exclusively evaluated ERS deployment on high-speed motorways and trunk roads, with a focus on heavy vehicles, which suggests there is a great knowledge gap to fill both regarding ERS use within cities for passenger cars and regarding integration between infrastructure for urban and long-distance use.

		ERS power per vehicle, kW					
Vehicle speed, km/h	1.76	20	30	**40**	50	60	70
	30	1.4	2.6	3.8	5.0	6.2	7.4
	40	0.8	1.7	2.6	3.5	4.4	5.3
	50	0.4	1.2	**1.9**	2.6	3.3	4.1
	60	0.2	0.8	1.4	2.0	2.6	3.2
	70	0.0	0.5	1.1	1.6	2.1	2.6
	80	-0.1	0.4	0.8	1.3	1.7	2.2
	90	-0.2	0.2	0.6	1.0	1.4	1.8

Table 8. Range gain in km per km driven on ERS, given varying power ratings of the road and varying vehicle speeds. At lower speeds, a vehicle can use a greater percentage of the power from the road for charging, and will remain on the road for a longer duration. Negative values indicate that the vehicle loses battery charge even while driving on the electric road.

Vehicle speed, km/h	ERS power per vehicle, kW: 20	30	**40**	50	60	70
30	42%	28%	21%	17%	14%	12%
40	55%	37%	28%	22%	18%	16%
50	69%	46%	**35%**	28%	23%	20%
60	83%	55%	42%	33%	28%	24%
70	97%	65%	49%	39%	32%	28%
80	111%	74%	55%	44%	37%	32%
90	125%	83%	62%	50%	42%	36%

Table 9. Ratio of total distance that must be covered by ERS for a vehicle to not run out of battery charge, given the per-vehicle power rating of the road and the vehicle's speed on the electrified road stretches. At lower speeds, a vehicle can use a greater percentage of the power from the road for charging, and will remain on the road for a longer duration. Values above 100% indicate that the vehicle loses battery charge even while driving on the electric road.

% of ERS energy during day	Electricity price, day/night offset %: -20%	0%	20%	**40%**	60%
75%	-0.25	-0.13	-0.01	0.10	0.22
82%	-0.25	-0.12	0.01	0.14	0.27
91%	-0.24	-0.09	0.06	**0.21**	0.36
96%	-0.21	-0.05	0.11	0.27	0.43
98%	-0.17	-0.01	0.16	0.32	0.48

Table 10. Difference in total cost of energy delivery using dynamic charging instead of static charging, for different ratios of day-time traffic, and for different day-night variations in electricity price. Values are in SEK/kWh and positive values indicate that static charging is cheaper by that amount. Total cost of energy delivery using static charging is around 3.5 SEK/kWh, including taxes, and is recalculated for each change in electricity price.

Supported fleet	ERS km: 100	200	500	**1000**	2000	5000
10%	0.17	0.27	0.59	1.10	2.11	5.16
30%	0.10	0.14	0.24	0.42	0.76	1.78
50%	0.09	0.11	0.17	0.27	0.49	1.10
70%	0.08	0.10	0.14	0.21	0.37	0.81
90%	0.08	0.09	0.12	0.18	0.31	0.65

Table 11. Difference in total cost of energy delivery using dynamic charging instead of static charging, for different lengths of the electric road system, and for different ratios of the county fleet that can rely on dynamic charging. Values are in SEK/kWh and positive values indicate that static charging is cheaper by that amount. Total cost of energy delivery using static charging is around 3.5 SEK/kWh, including taxes.

Figure 16. Map of roads in Stockholm Municipality with line thickness proportional to (AADT_heavy * 4 + AADT_light) / mean_speed_kmph, i.e. weighted total time spent by vehicles on each road km. 70 km/h and 10% heavy traffic of total AADT were used to fill in missing data. The roads where most energy can be transferred in a day include motorways, frequently congested inner-city streets and streets with low speed limits but relatively high traffic. Original data from Stockholm's data portal, "Årstrafik", from May 14, 2021[23]. Basemap © OpenStreetMap contributors.

Pros and Cons of Dynamic vs. Static Charging

While our analysis indicates that dynamic and static charging can achieve similar cost, there are several other factors that make the solutions very different:

Mandate: Implementation of static charging requires highly distributed decision making, i.e. hundreds of thousands of independent actors must invest in and maintain their part(s) of the whole. An electric road system is built on public roads and only requires decisions by a few public-sector institutions. At the same time, static charging is seen as an established solution and dynamic charging requires public approval. Quicker infrastructure deployment will lead to

[23] https://dataportalen.stockholm.se/dataportalen/GetMetaDataById?id=LvFeature5680392

faster electrification of the vehicle fleet and greater cumulative value generation, but it is not clear whether static or dynamic charging will be quicker to implement. It is also unclear how a political switch in policy would be received by the public and by recent investors in static charging infrastructure.

Implementation: As seen in the chapter on static charging infrastructure, cost grows significantly if more charging infrastructure is installed than what is necessary to deliver energy to the vehicles. The same is true for combinations of static and dynamic charging. It would be unwise to first build out static charging to full coverage, to later install a large ERS network, as the city does not need both. This means that a decision must be made very soon regarding what direction to take. Once a direction is set, the infrastructure should be deployed as quickly as possible to minimize the sales of new ICEVs and maximize the rate at which the vehicle fleet is electrified. Both strategies that rely fully on static charging and those that mix dynamic and static charging allow for gradual refinement of infrastructure placement and quantity during the build-out stage.

Standards: Competing standards is a current issue in the static charging market and dynamic charging is worse. OEMs offer solutions based on incompatible proprietary technologies and standards are either still under development or absent. We cannot recommend the city to chose any particular interface for dynamic charging (and/or on-street static charging), but rather advise an open dialogue with the Swedish Transport Administration to ensure that the city uses whatever standard that will be selected for the national motorway network.

Power distribution and supply: Dynamic charging transfers almost the entire demand for electricity to day-time, coinciding with peak traffic. As discussed in the chapter on static charging, this will most likely require strengthening of the electrical grid. However, the number of grid connection points for an electric road will be few, approximately one every 20 km, with each connection able to provide around 10 MW. Substantially fewer grid upgrades should be needed for dynamic charging than for day-time static charging, though Ellevio, the local grid operator, has been unable to confirm this hypothesis. Should electricity production (not distribution) become a limiting factor, it may be easier to rapidly increase day-time/peak production (solar, wind and grid storage) than night-time/base production (hydro and nuclear).

Equality: Dynamic charging infrastructure for passenger cars would be installed on main roads and accessible to all who use the roads. If widely deployed, this ensures that all cars in a region have equal access to charging, regardless of where they park. No booking is required and the system naturally adapts to provide more charging for vehicles that are used more intensively. As it makes little sense to vary the cost of dynamic charging in space, cost is also equal for all. Letting the charging cost vary with the spot price of electricity or the traffic density provides a natural incentive to flatten the peaks of road use, which may reduce congestion on the road network.

Integration with national charging infrastructure: Passenger car traffic in Stockholm County has been treated in this report as a closed system, without assuming that significant traffic enters or leaves the region. In reality, most passenger cars make infrequency but important long-distance trips on the national road network. As national deployment of dynamic charging infrastructure is being considered for the core motorways, dynamic charging also within Stockholm would provide seamless integration between short and long-distance journeys.

Private vs. commercial traffic: Spot pricing of electricity (and possibly grid use) creates an incentive for night-time charging. With dynamic charging, this means night-time transports, while static charging better aligns with the current pattern of night-time inactivity. In general, dynamic charging is much better suited for 24h operation and autonomous vehicles with uninterrupted use. Dynamic charging allow all road users to share the cost of infrastructure, which is difficult with static charging.

Flexibility of future city planning: It is of interest to the city to find ways to gradually reduce both on-street parking and inner city car traffic. This implies that the city would like to avoid investing too much in chargers for on-street parking spaces. Scenario 4 in the static charging chapter strived to minimize on-street charging, which then necessitated that cars that depend on this type of parking both day and night relocate much of their parking to public parking garages. Dynamic charging on main roads could also be a way to retain flexibility in city planning.

Socio-Economic Result

To conclude our analysis of charging infrastructure for passenger cars in Stockholm, we bring together the results from the value estimation of passenger car electrification, the forecast of local EV sales, the recommendation of static charging infrastructure placement and the resulting cost estimation of charging. These data together let us estimate the cumulative socio-economic value of electrifying the passenger car fleet within Stockholm County.

We assume that access to charging infrastructure is a prerequisite for purchasing an electric vehicle, i.e. that charging infrastructure of some type must be deployed quickly and densely enough to enable the desired transition to an electric fleet. As purchasing decisions are made also in the used car market, charging infrastructure must be ubiquitous throughout society, else BEVs will leave the region after their first owner.

We assume that charging infrastructure should be installed at a minimum rate (Figure 17) corresponding to the total ratio of electrified transport work, but shifted two years earlier to have time to influence vehicle buyers. Electrified transport work includes all driving with BEVs and 70-90% (2020-2040) of the transport work by PHEVs, which are likely to make up a significant share of the local car fleet until the early 2030s. PHEVs have not been a focus of this analysis and we believe they will become obsolete when charging becomes ubiquitous and BEVs have a lower price point.

Annual and cumulative socio-economic results including and excluding the value of reduced CO_2-emissions are presented in Figure 18 and Figure 19. Charging infrastructure costs are based on scenario 1 for static charging, described in Table 4. The socio-economic result is calculated as the sum of reductions in internalized and externalized vehicle costs (for the electrified part of the fleet) minus the levelized cost of infrastructure. Levelized infrastructure costs include the initial investment, maintenance, operational fees and operational overhead. The cost of electricity is included in the vehicle cost calculations.

As infrastructure is needed to realize the cost savings in the fleet, there is an opportunity cost associated with delaying the transition through a slow deployment of charging infrastructure. This opportunity cost can be calculated by assuming a faster or slower rate of growth in the ratio of BEVs among newly registered cars (i.e. shifting the black curve in Figure 8 along the horizontal axis). Resulting cumulative savings after deduction of infrastructure costs from 2020 until 2030 and 2040 are presented in Figure 20. The opportunity cost of delaying the transition is approximately 16 billion SEK for every year of delay, represented by the slope of the lines. The opportunity cost is approximately 7 billion SEK if counting only internalized costs, i.e. if excluding the socio-economic value of untaxed CO_2 emissions.

We note that the calculated *yearly* opportunity cost of delayed infrastructure installation (approx. 16 BSEK) is in the same order of magnitude as the calculated total capital cost of the infrastructure itself (approx. 8-14 BSEK) and not far from the total cumulative infrastructure cost until 2040 (approx. 30 BSEK). It therefore seems wise to compare charging infrastructure strategies as much in terms of total investment cost as in terms of how quickly they can enable electrification.

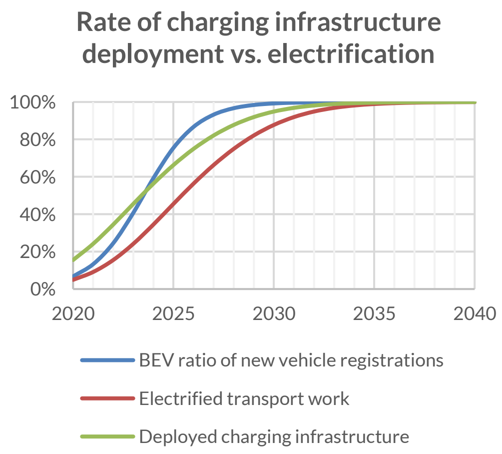

Figure 17. Suggested rate of deployment of charging infrastructure. BEV ratio of new vehicle registrations corresponds to the forecast in Figure 8 and deployed charging infrastructure is the same data series shifted two years earlier. Electrified transport work is used to calculate the impact of the infrastructure.

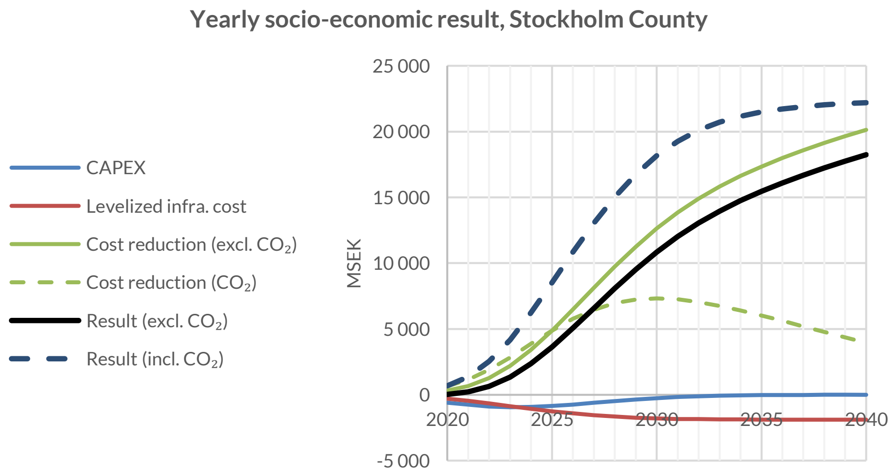

Figure 18. Estimated *annual* socio-economic result (vs. retaining the system of ICEVs) for all proposed charging infrastructure in Stockholm County, if placed according to Scenario 1 in Table 4 and installed at the rate shown in Figure 17.

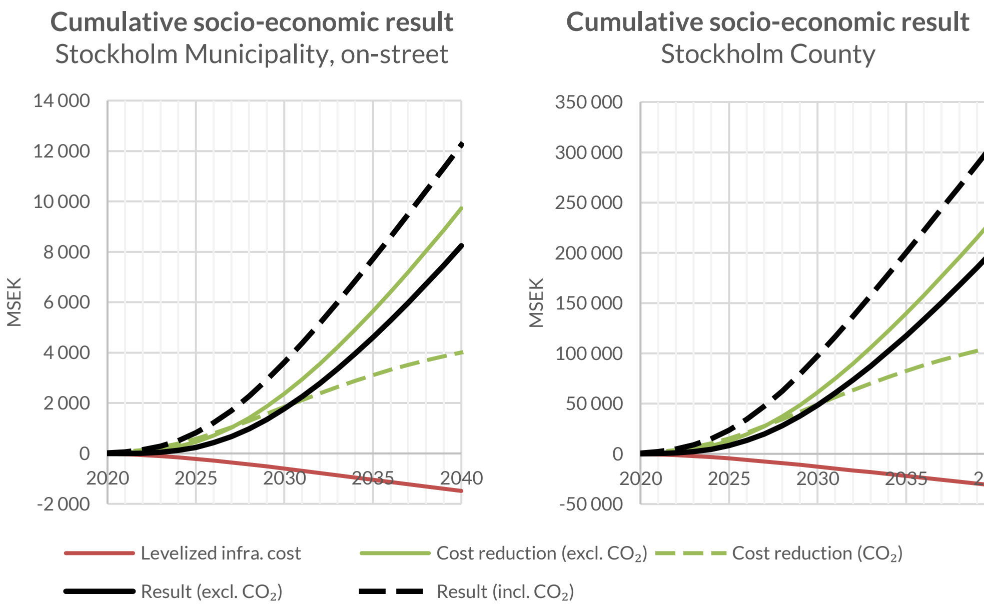

Figure 19. Estimated *cumulative* socio-economic result (vs. retaining the system of ICEVs) for the proposed on-street static charging infrastructure within Stockholm Municipality (left) and for all proposed charging infrastructure in Stockholm County (right), if placed according to Scenario 1 in Table 4 and installed at the rate shown in Figure 17.

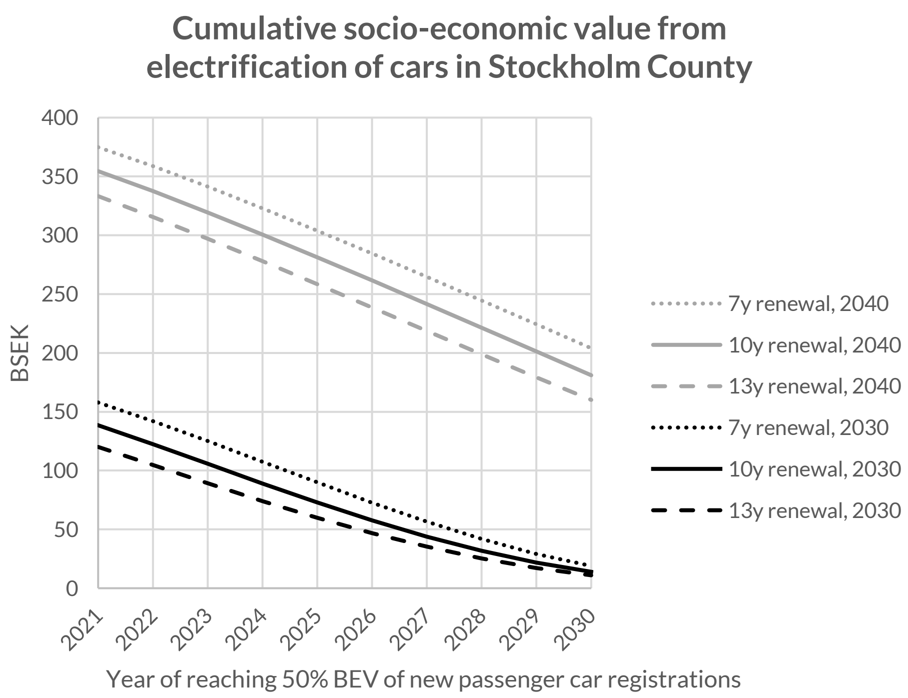

Figure 20. Sum of annual cost savings in the vehicle fleet until 2030 and 2040 from electrification of passenger cars in Stockholm County, after costs of charging infrastructure and including externalized costs of emissions. The horizontal axis corresponds to a shift of the "BEV ratio of sales" curve in Figure 8, while the dotted and dashed lines indicate the sensitivity to the estimate of the fleet's rate of renewal. Each year that Stockholm's transition to EVs can be sped up is worth approximately 16 billion SEK, represented by the slope of the curves. Default values are mid-2026 and renewal every 10 years.

Discussion

Fairness and Incentives

Because the opportunity cost of delaying electrification is so great, it is important to identify what holds back infrastructure deployment in the region. While identifying such bottlenecks has not been in focus for the work, Figure 4 shows that electrification has thus far not generated much value in terms of *internalized* cost savings, with the exception of high-end cars with high annual mileage. Private investors in charging infrastructure cannot make a profit by contributing to lowered emissions, as long as the cost of those emissions is externalized (except through public grants and subsidies).

Costs of battery-electric vehicles have been decreasing and will continue to decrease, and BEVs *on average* reach cost parity with ICEV from a total cost of ownership (TCO) perspective around model year 2020. This is important, as the cost difference between ICEVs and EVs works as a price cap for vehicle charging if EVs are to result in overall cost savings for the vehicle buyer. However, while the room for private sector profit margin on charging is growing, the coming decade will remain characterized by that the public sector has more to gain from vehicle electrification than private investors do. The public sector is the only investor who can possibly include the externalized social cost of carbon in its accounting and therefore the public sector may be the only actor that can make rapid electrification of cars happen. The externalized cost of greenhouse gas emissions from ICEVs is so great that, if such accounting is allowed, the public sector could offer charging at negative prices and still make a profit.

Another type of externalized cost is that of land use along city streets. Non-cable charging interfaces were shown to reduce overall system costs if more than 10% of the parking spaces are equipped with chargers, but lead to increased costs for the user of the charger, as vehicles must be equipped with a new charging interface. Should the city opt for using non-cable interfaces, it could consider subsidizing the additional hardware in the cars, as the value of choosing this solution (minimizing land use) only partially benefits the people who depend on this charging infrastructure.

The analysis in this report points to that battery electric passenger cars are going to be much cheaper to both purchase and operate in 2030 than ICEVs are in 2020. This puts the city in a dilemma. Should the city allow transportation by passenger car to become cheaper than today in relation to public transport? Should EVs alone be taxed to keep their costs high, which would reduce the economic incentives for electrification? Should parking fees and congestion charges be raised to compensate for the reduced operative costs of passenger cars, which would disproportionately hit those who must wait the longest for a transition to EVs, e.g. those who can only afford extensively used cars or have special needs? We have no answers to these questions, but note that it is time to begin debating the challenges politically.

Resiliency

None of the scenarios for charging outlined in this report include a dependence on fast charging at energy stations. This is because we do not see how it would be possible to provide this form of charging at costs as low as those we achieve with infrastructure placed elsewhere. Is there then no market for fast charging?

There probably is, but motivated not by any normal state, but by resiliency to deviations from normal. Centralized fast charging can be a way to enable any resident within the city to buy an electric vehicle if they have the means to do so, without having to wait for chargers to become available at their preferred place of parking. Centralized fast charging may also be needed to meet peaks in demand before national holidays, and perhaps to enable sudden long-distance travel by car for those who would otherwise need to wait a few days for charger access. Energy stations also work as back-up for local power outages.

Synergies and Future Proofing

While they have not been a focus of this report, there are other vehicles on the roads than private passenger cars. Utilization patterns for vehicles used in commercial traffic (light, medium and heavy) differ significantly from those represented in our models and we cannot see a way to share static charging infrastructure (except at energy stations) between private and commercial vehicles.

Sharing of dynamic charging infrastructure would be trivial in all cases where both share the same roads. The calculated cost per kWh of dynamic charging that was reported in this report is based only on utilization by passenger cars. Inclusion of commercial traffic as users would only marginally raise the cost of the infrastructure, thus the infrastructure cost per user would likely decrease by 10-50% for both private and commercial users (varying by commercial share of total road use). The overall effect on total cost of charging would still be relatively small, as the main costs are electricity and taxes. A dynamic charging network within the city would make travel by car to other cities much easier if decisions are made at the national level to install dynamic charging on motorways of a type that supports passenger cars.

Many major cities around the world, including Stockholm, have ambitions to allocate less land to parking. This implies fewer cars, but not necessarily less travel by car. Distributing the same traffic over fewer cars would have little effect on the need for charging infrastructure, as the same energy needs to be supplied every day.

Regulatory Obstacles

Regulatory questions have been out of scope for this work. A handful of issues that we find worth including have still been mentioned in passing in stakeholder correspondence or meetings.

The grid operator is currently prohibited through legislation to install energy storage within the electrical grid. Batteries and other forms of energy storage are plummeting in cost and to not use these technologies for load balancing, peak shaving and other forms of grid management would be wasteful.

The grid operator claims that the city imposes overly strict rules on digging, which raises the costs of installing of new grid connections and outdoors charging infrastructure above those in comparable cities. According to the grid operator, these rules should be relaxed.

Fees paid to the electrical grid operator are of similar magnitude to the costs of installing and maintaining the charging infrastructure itself. These fees are based on energy consumption and peak power demand, where only the cost of energy consumption differs by time of use. As the grid has available capacity during some times of day but not others and adding capacity is costly both for the grid operator and charger operator, it may be beneficial to have dynamic pricing also of cost components related to peak power. This would incentivize placement of infrastructure that leads to off-peak use.

All arrangements where a parking space is reserved for use by a single car result in increased costs of charging, sometimes substantially. To avoid having to install charge points at every parking space in a garage or large lot, we advocate for reserved access to parking rather than to individually reserved spaces.

City parking garages are not currently open to non-reserved parking at night. If chargers in parking garages are to complement on-street chargers, these rules must either be relaxed of it must be possible to gain temporary access. It seems logical to integrate such a system for temporary access with a booking system for chargers.

Limitations

This is a single-author report that recommends several billion SEK of rapid investment to transform passenger car traffic for decades to come. The analysis has several limitations that are worth considering and that could be resolved in future work.

Several improvements could be made regarding the accounting practices used when calculating socio-economic costs and benefits. Vehicle CAPEX is annualized and added to OPEX to get an average cost of vehicle use in each year. This results in that CAPEX is assumed to change over the lifetime of a vehicle, at the same rate that technology advancements apply to newly sold vehicles. Interest rates and inflation are not accounted for, and there are no conversions to present value of future costs or incomes.

Moreover, fleet sizes are estimated for the central model year of 2030 and then kept constant over the model period. Car use and resulting traffic volumes are also held constant, despite that the analysis concludes that electrification is likely to generate a sharp decline in the cost of passenger car use.

There are numerous assumptions about future developments of costs and performance for both combustion engine and battery electric cars. The sources used are believed to be credible, but there is great uncertainty around these numbers. Regular revision of these assumptions to match actual development is recommended, as they have great impact on the estimated socio-economic value of electrification. Impactful parameters include annual distance and days of car use, vehicle sales price, battery pack costs, fuel and energy efficiency, fossil fuel, biofuel and energy costs, fossil CO_2 emissions from biofuels, and the social cost of carbon.

Around 60% of the levelized cost of passenger car use is from the purchase price of the vehicle itself, thus its annualization period significantly affects the estimated levelized cost. Years of use have been assumed to both remain constant over time and be equal for ICEVs and BEVs. It does not seem unreasonable to believe that this may not be the case, in particular during a period of rapidly changing costs. A difference in expected lifetime between the vehicle types will have a fairly strong impact on the calculated socio-economic result. May factors could influence this, including cost development, potential restrictions imposed on export of ICEVs, new options to convert ICEVs into hybrid or battery-electric vehicles, or better options for battery upgrades in existing PHEVs.

Denser charging infrastructure reduces the minimum viable battery capacity in vehicles and could make vehicles cheaper. This effect could be substantial, possibly even greater than the total cost of all charging infrastructure, but time limitations have not permitted assessment of this effect.

The way PHEVs are handled in the calculations could also be improved. There is currently no separate cost model for PHEVs, despite that they are forecast to make up over 30% of the fleet during a few years around 2027. PHEVs are partially included to estimate total electrified transport work, which is then used to calculate both the deployment rate of charging infrastructure and the socio-economic value generated from electrification. While somewhat inaccurate, BEV CAPEX is not assumed to become significantly cheaper than ICEV CAPEX until after PHEVs have mostly disappeared, thus it is not believed that this methodological simplification has much impact on the conclusions of the report. The greatest uncertainty related to PHEVs is around their usage pattens of static charging infrastructure; who will own a PHEV, at which location types will PHEVs primarily charge and how much use will they increase occupancy of shared infrastructure until they are phased out? The assumption is that

PHEVs require charging after every use and therefore only appeal to buyers with access to a private charger.

A great deal of uncertainty surrounds future electricity prices. Society's demand for electricity is expected to greatly increase over the coming decades, at the same time as energy storage is expected to decrease in cost and renewable energy production, which tends to peak during the day, is expected to be substantially increased. If this results in smaller differences between night and day-time costs of electricity, night-time charging loses much of its cost advantage and the case for electric roads becomes stronger.

Opting for dynamic charging rather than static charging does appear to have many qualitative benefits that align well with the long-term city-development goals. However, it has been beyond the scope of this report to assess whether (all or any of) the technologies are actually ready for deployment. The greatest uncertainties from a socio-economic perspective are whether the charging interfaces can deliver sufficient power for charging to take place also at high speeds, what the cost of the hardware in each car will be, and if sufficient manufacturing capacity exists for hundreds or thousands of km of road to be electrified within a few years.

Figure 12, Figure 20, Table 10 and Table 11 give a sense of the total size of effects from changes in demand, but demand has not been modelled. Pricing (including indirect costs) will have effects on demand, including both the demand for passenger car use, demand for EVs vs. ICEVs, and the relative demand for charging at different locations (e.g. on-street, in parking garages, at work, at the shopping mall, dynamically on the road or at a an energy station). Small differences in cost for different solutions may also have great impact on the interest of private parties to invest, as solutions with lower costs vs. the competition can allow profit margins to be increased. It is unclear how the public sector would price charging if it is the investor and operator, as it wishes to incentivize rapid electrification of the car fleet to get rid of tremendous externalized costs from combustion fuels and may therefore find it logical to price use below costs, at least during a transition period.

Finally, the report offers no help regarding exactly where to install charging infrastructure. It has been clear from stakeholder conversations that grid installation costs, opportunity costs of land use, parking occupancy rates and the age of the car fleet (i.e. the time until EVs will be available) vary greatly on a very local scale. Identifying these local conditions (at scale) and adapting to them remains to be done, regardless of whether the city decides to go for static or dynamic charging or a mix of the two.

Generalizability

All analysis within this report has been conducted with the city of Stockholm in mind. The challenges faced by Stockholm are not unique, but several parameters are used in the models that will have different values in other cities and countries. These include energy costs, fuel costs, CO_2, VAT and other taxes, the agreed social cost of carbon, digging costs, grid substation density, grid fees, car density, car use, traffic patterns and ratios of parking types. Enclosed with the report is a spreadsheet containing all calculations and figures. It is recommended to spend some time to adjust the parameters there to fit the local context before specific conclusions are extrapolated to other contexts.

Conclusions that should generalize are overall density of static charging that is needed to support the fleet of passenger cars; that electric road systems can be a viable alternative to static charging for powering passenger cars in cities; that EVs will become cheaper than ICEVs (year of cost parity may differ); and that EV adoption is held back primarily by externalization of ICEV emissions and lack of charging infrastructure. All qualitative sensitivity analyses should also hold.

Recommendations

The following recommendations are provided to the County and Municipality of Stockholm based on the analysis in this report.

Prioritize speed: Electrifying the passenger car fleet within Stockholm County has the potential to generate *annual* socio-economic cost savings worth approximately 18 (11)[24] billion SEK by 2030 and 22 (18) billion SEK by 2040, after deducting the levelized cost of the necessary charging infrastructure. The *cumulative* value from 2020 is approximately 100 (50) BSEK by 2030 and 300 (200) BSEK by 2040. Each year that the transition is delayed or accelerated is associated with an opportunity cost of approximately 16 (7) BSEK. Cumulative costs of investment and operation of charging infrastructure are calculated at 13 BSEK by 2030 and 31 BSEK by 2040, of which roughly half is OPEX. Return on investment (ROI) at the county level is estimated at 750% (400%) at the county level by 2030 and 1000% (650%) by 2040. ROI for municipal street charging is estimated at 600% (200%) by 2030 and 800% (550%) by 2040. When comparing different strategies to achieve electrification of the passenger car fleet (and likely all road vehicles), speed of implementation should be considered alongside differences in cost.

Given that EVs already make up such a large and increasing ratio of new registrations, policy instruments designed to incentivize early retirement of ICEVs would likely be a very effective way to quickly reach >95% EVs on the roads.

Incentivize early ICEV retirement: The passenger car fleet within Stockholm County is renewed approximately every 10 years, but individual cars likely have longer lifespans. Incentives that selectively shorten the average lifespan of cars with internal combustion engines would be particularly effective at speeding up the overall transition to electric vehicles, with effects beyond the capital region.

Subsidies, public investment or taxed emissions: The forecast in Figure 8 indicates that approximately 90% of the traffic will be electric by 2030, unless poor access to charging infrastructure hinders this development. Finding ways to install this infrastructure on time is of great importance, and may require deviations from the current policy that charging infrastructure should be funded by private investors. Private investment can be profitable, but as long as internal combustion engine cars remain heavily subsidized through undertaxation of fossil greenhouse gas emissions, subsidies of equal magnitude are needed to bring incentives for electrification by the private sector in line with the incentives for the public sector. Great care should however be taken to not alter the relative competitiveness of different charging solutions, as this would leave the city with suboptimal infrastructure long after the subsidies have been removed.

Investigate limits in electricity production: Charging of a fully electrified passenger car fleet will increase total demand for electricity by approximately 500-700 MW within Stockholm County during the peak time of charging, which can be day, night or during peak traffic. Around 90% of this level is expected to be reached by 2030, equivalent to an addition of approximately 50-70 MW every year until 2030. Investigate whether this will be a challenge for energy producers and if so, at what time of day it is most feasible to increase electricity production to the desired levels. Placement of charging infrastructure can very effectively shift

[24] Values in parentheses are excluding the value of reduced untaxed fossil greenhouse gas emissions from fuel combustion. The analysis assumes a gradually increasing ratio of biofuel use in combustion engine cars and slowly increased taxation of GHG emissions, which contributes to a gradual internalization of emission-related costs. €1 is approximately equal to 10 SEK.

the total power demand between day and night (static charging) to correlate with traffic density (dynamic charging).

Minimize static day-time charging: If energy production permits, try to minimize static day-time charging, as heavy use of static day-time charging will necessitate extensive and expensive upgrades throughout the electrical distribution grid. Sufficient unused grid capacity is available at night as long as load balancing strategies are used, and while grid upgrades will be needed for dynamic charging, they are not believed to be as extensive as for day-time static charging as the connection points are far fewer.

Dynamic grid fees: Subscription fees to the electrical grid are of the same magnitude as levelized costs of infrastructure and initial grid connections. As increases in night-time use of the grid will not create the same need for upgrades as increases in day-time use will, it would make sense to more extensively differentiate the grid fees by time of day, to incentivize balanced use of the grid. More balanced use would also increase overall utilization of the same grid infrastructure, which should lead to lower costs per user.

Avoid over-investment: Table 4 on page 32 compares four possible placement scenarios for static charging infrastructure. It is not advised to build chargers at much greater density than indicated, as this raises cost per user without adding any significant benefits (see the point "Explore battery vs. infrastructure trade-offs" below for a caveat regarding this recommendation). The network model developed for this analysis makes it possible to verify that a placement strategy results in similar charger access rates and similar cost of charging for different demographics within Stockholm County. Fast charging at energy stations is not used as a default method of charging for any segment of the car fleet in any of the scenarios, due to high costs. Public parking garages are used to supplement night-time charging at on-street parking spaces in all scenarios.

Chargers at 10-15% of on-street parking spaces: Table 7 lists the recommended numbers of static chargers to install at on-street parking spaces per district within Stockholm Municipality. The recommended levels are 10% of parking spaces within the inner city and 15% in residential areas, installed in groups of 30 and 20 chargers, respectively. Grouping chargers into sites with a shared grid connection enables load balancing and greatly reduces costs. Total investment cost to install the chargers is estimated at 370 MSEK, with a levelized cost of 90 MSEK per year (includes annualized investment cost plus maintenance, grid fees, opportunity costs of land use and operational overhead). Presence of dynamic charging infrastructure could potentially eliminate the need for static chargers on public land.

Booking system for chargers: All recommendations regarding deployment of public chargers are based on the introduction of an efficient booking system. Booking is needed to ensure that all users have access to charging and to keep infrastructure costs down. An example of a simple but viable booking system would be to allow up to one reservation per car, for up to 12 hours at a time. Restricting who can use the chargers or limiting the length of charging sessions to increase turnover brings no clear benefits.

Minimize land waste: Static charging using cable interfaces and installed at on-street parking spaces is associated with a high opportunity cost of occupied land. If more than approximately 10% of on-street parking spaces are equipped with chargers, it becomes cost saving to avoid cable interfaces and instead install conductive or inducting interfaces that deliver electricity directly from the road surface. These are the same charging interfaces as those used in electric road systems. The new charging interface necessitates installation of additional hardware in all vehicles that want to use the chargers. Subsidizing this hardware would make sense, as the cost saving does not primarily go to the car owner. Day-time users of the chargers would then also need the same in-car hardware.

Explore battery vs. infrastructure trade-offs: There is still a focus today on increasing the availability of charging infrastructure to the point where BEV operation becomes at all feasible. Going forward, it will become important to understand the trade-offs on total system cost between density of charging infrastructure and the capital investment in battery capacity in cars. According to the calculations in this report, the total annualized cost of passenger car batteries (at 100% fleet electrification) for Stockholm County is approximately 2-4 times the sum of annualized costs of all charging infrastructure and grid connections. It is possible that additional socio-economic cost savings could be achieved by further increasing the charger density beyond the recommended levels, if this results in even greater savings through encouraging residents to buy vehicles with smaller battery packs. Modelling this feedback effect has been beyond the scope of this project.

Further investigate dynamic charging: Dynamic charging using so-called Electric Road Systems (ERS) installed on main roads throughout Stockholm would likely result in similar cost of charging as installing static chargers. Benefits of dynamic charging include synergies with commercial light and heavy traffic, greater public sector decision mandate, greater equality of charging in terms of access and cost and integration with a potential future national ERS network. All strategies for charging infrastructure placement that do not involve chargers installed at on-street parking spaces avoid issues associated with reduced flexibility in future city planning. Dynamic charging may be one of the most feasible strategies to achieve that. The report does not asses how dynamic charging would interact with static charging infrastructure, what road distance to electrify, whether dynamic charging would be quicker to build out than static charging, whether the technology is mature enough, or whether a future national ERS network would support passenger cars. An indication of which roads would be suited for dynamic charging infrastructure is given by Figure 16. Vehicles that charge their batteries on an electric road can operate on non-electrified parts of the road network, though static chargers would be needed beyond (half) the range limits imposed by the battery capacities of the vehicles. The city is advised to monitor and possibly participate in the national planning and assessment of ERS on the motorway network.

Maintain and reuse cost models: All parameter assumptions, calculations and figures used in this report are provided as a supplementary Excel spreadsheet. With time, better parameter assumptions will become available and values in the spreadsheet can be update to understand the impact that the change in input has on model output. What-if-analyses can be conducted in the same way, for instance to assess different placement strategies of static charging infrastructure in terms of the quality metrics in Table 4. The network model of vehicle mobility that is used in the spreadsheet would scale and could be generalized to model flows between individual districts within the city, rather than the ten coarse location types used in this report. Necessary flow data could potentially be extracted from Trafikanalys or from purchased floating car data (GPS traces).

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