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Charging Infrastructure Recommendations for Cities Targeting Full Passenger Car Electrification, Based on a Case Study of Stockholm County

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Executive Summary

We present a novel methodology for calculating the density of charging infrastructure required to enable electrification of all passenger cars in a large geographic region. We combine this method with models of charging infrastructure cost, forecasts of levelized costs for operating combustion engine and battery electric cars and forecasts of market penetration, to calculate the socio-economic value of passenger car electrification over the 2020-2040 period. Recommendations for urban regions are derived based on application of the method to Stockholm County, Sweden. Electrification is shown to generate long-term savings of up to 1800 euro per car-year and the opportunity cost of delaying the transition by a single year is comparable to the full cost of deploying the infrastructure that enables the shift. Large-scale deployment of dynamic charging is a cost-viable alternative to static charging for full electrification of urban passenger car fleets.

Keywords: infrastructure, municipal government, optimization, passenger car, strategy

1 Contribution

Cities around the world seek cost-efficient strategies to reduce greenhouse gas and other emissions from road traffic, partly through electrification. New charging infrastructure must be built to enable this transition, but there is little agreement on where charging infrastructure should be installed and how much is required. Cars parked on city streets in areas with multi-family homes have turned out to be particularly challenging to electrify, as chargers placed here would increase the cost of city maintenance and permanent parking on valuable land. Cities like Stockholm, Sweden, are also finding that private investment in new charging infrastructure is slower than anticipated, raising the question what role the public sector must play in the transition.

We provide a novel methodology for estimating the socio-economic value of electrifying a city-sized fleet of passenger cars, i.e. fully replacing internal combustion engine vehicles (ICEVs) with battery electric vehicles (BEVs). Compared to prior work, the main strength of our methodology is its combination of transparency of assumptions, ease of application, and inclusion of network dependencies in the charging infrastructure, i.e. that an increase in charging infrastructure in one location will impact the use of charging infrastructure elsewhere. The methodology is applied in a case study of the region of Stockholm County, Sweden, for which we also calculate the substantial opportunity cost associated with delaying or accelerating the transition to an electrified car fleet. The calculations are implemented in a Microsoft Excel spreadsheet to allow for easy application to other cities.

For static charging infrastructure, we identify the density and number of charging points in different regions of the city that together form a charging network capable of delivering the electrical energy consumed by a fully electrified vehicle fleet in operation. Different configurations of charging infrastructure that all meet the basic charging requirements are compared in terms of total cost, fairness across different population groups and aggregate load on the electrical grid during different times of day. We also estimate the rate of installation of charging points necessary to avoid holding back the rate of electrification of the vehicle fleet.

This paper is a summary of a longer report written on behalf of the City of Stockholm. Some parameter assumptions have been updated to reflect global market developments since the longer report was published. The full report goes into greater detail regarding electrification of different market segments of passenger cars, different stakeholder groups' preferences for charging at different locations, and comparison of static charging infrastructure (”charging poles”) with dynamic charging infrastructure (”electric roads”) in urban settings.

2 Method Overview

Our metric used for the value of passenger car electrification is the reduction in total cumulative socio-economic cost of operating the transport system, compared to a base-line scenario of continued reliance of ICEVs. This is calculated by estimating the reduction in total levelized costs of operating the vehicle fleet and subtracting the total cost of charging infrastructure. Fleet operating costs are calculated by multiplying the estimated difference in annualized per-car cost of ICEVs and BEVs, the number of passenger cars in the region, and forecast ratio of the fleet that is made up of BEVs. Charging infrastructure costs are modeled as a function of site location, configuration, and pattern of use. We identify cost-minimizing configurations that are also attractive in terms of resilience, fairness and impact on the electrical grid by modeling the network dependencies of charging infrastructure, and we set the rate of infrastructure installation to precede the car fleet electrification rate by one year.

The opportunity cost associated with accelerating or delaying fleet electrification is estimated by adjusting the rate of BEV adoption in the fleet and comparing the total cumulative system cost over the studied period. Due to space limitations, the calculations are not described exhaustively in this paper. We instead provide these as a Microsoft Excel spreadsheet (on request) in which all parameter assumptions can be inspected and adjusted to match the geographic region where the model is to be applied. ICEVs are not differentiated by fuel type in the calculations.

3 Calculation Steps

3.1 Difference in Per-Vehicle Cost, BEV vs. ICEV

Electrification of passenger cars is motivated by an assumption that this would be socio-economically beneficial, which we quantify as that internalized plus externalized levelized costs of operating the transport system will be lower if future cars are electric than if those cars run on internal combustion engines. Internalized cost components that electrification is assumed to change are purchasing and maintenance of vehicles, fuel/energy, and its distribution. Externalized cost components are primarily emissions and land use. Electrification deprives the state of income from fuel taxes and to simplify comparison, we keep total tax revenue constant in our model and transfer the taxes from a per-liter fee to a per-kWh fee. Explicitly designated CO_2-taxes are scaled with emissions.

Changes in insurance costs and the socio-economic value of reduced traffic noise are not accounted for. Traffic noise has a documented effect on housing prices, human health, wildlife behavior and indirectly on whole ecosystems influenced by wildlife behavior. Furthermore, we omit costs of emissions associated with manufacture of all vehicle parts except batteries, as well as costs of emissions other than greenhouse gases. The lifespan of a car has substantial impact on the levelized cost of operating the transport system, but as we have been unable to find any reliable source for how electrification affects the lifespan of cars, we use the same value for both vehicle types.

Figure 1 shows expected cost development for each type of vehicle, using assumptions for costs and vehicle operation representative of Stockholm County, Sweden. Internalized cost parity occurs near 2020 and demand for electric vehicles can be expected to grow substantially in the following years. We assume a minor gradual increase in cost of manufacture of ICEVs, due to tightening emissions regulations and reduced sales volumes due to loss of market share to BEVs. Due to increased sales volumes and competition, as well as maturing manufacturing processes and product designs, BEVs (excluding their batteries) are expected to decrease in price. We use battery pack prices of 140, 70 and 54 USD/kWh for years 2020, 2030 and 2040. These numbers were extrapolated from historic data from BNEF [3]. Costs for repairs and maintenance are assumed to be substantially lower for BEVs than for ICEVs.

Fuel costs for ICEVs are substantially greater than electricity costs for EVs. However, at the time of writing (April 2022), the market prices of petrol, diesel and various biofuels have doubled over the past year, and there is significant uncertainty regarding fuel costs. We have used fuel prices of 6 SEK/liter for fossil fuels and 15 SEK/liter for biofuels, before taxes, which are both below current market prices, but close to average historic level for fossil fuels and near average historic level for biofuels. Despite assumed constant product costs, we expect combustion engine fuel prices for consumers to increase substantially, as Sweden has a policy in place to gradually increase the ratio of biofuel in petrol. In the calculations, the biofuel ratio is 30% in 2020, 55% in 2030 and 70% in 2040. We also assume that CO_2 taxes will be raised gradually from around 12% of the nationally accepted Social-Cost-of-Carbon (SCC) of €700/ton in 2020 to around 40% in 2040. Together, these changes reduce the socio-economic cost of ICEV use, but raise user costs. Using a lower SCC value, as is done by most countries, would reduce the calculated externalized CO_2 emission costs. Battery production for local cars is expected to move from China to Northern Europe during the period, which gradually lowers CO_2 emissions from batteries.

The cost of energy delivery (installation, maintenance and operating fees of charging infrastructure and grid connections) will be determined in a later section and will vary depending on the infrastructure's type, placement, and utilization. A placeholder cost of energy delivery is included in figure 1. Costs associated with combustion fuel distribution are included in the cost of fuel.

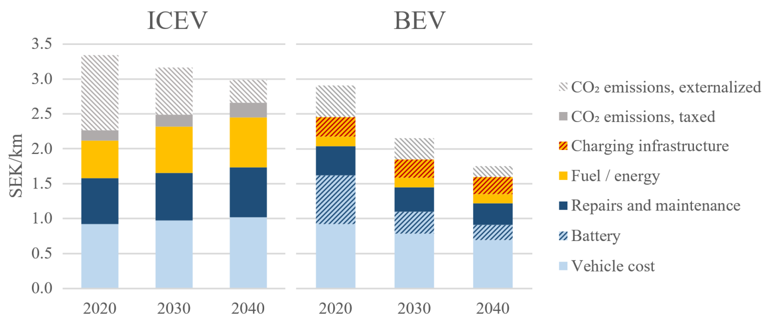

Figure 1: Itemized comparison of levelized costs of operating ICEVs and BEVs in Stockholm County. Externalized CO_2 costs are from combustion fuels, electricity and battery production.

3.2 Rate of Vehicle Electrification

The previous section estimated the cost savings resulting from electrification of a single car. To estimate the total value at transport system level, we also need estimates of the total number of cars and the rate at which these are replaced with BEVs.

Data for Stockholm county on new vehicle registrations by energy source, as well as total number of vehicles in use, are available from Statistics Sweden [2]. Sales of electric vehicles (battery-electric, plug-in hybrids and hybrids) has gone from 20% of all new passenger cars in mid-2019 to 70% in the first quarter of 2022. Sales of BEVs have climbed from 5% to 30% in the same period. Extrapolating this series using a logistic function ('S-curve') gives us an estimate of reaching 90% BEV of all new passenger car registrations in the beginning of 2025. These figures represent the inflow of new vehicles into the regional car fleet.

The total number of passenger cars in the region is approximately one million and that approximately 10% of the fleet is replaced every year, numbers that have remained relatively stable for the past decade. However, national statistics also report that the mean age of passenger cars in Sweden is ten years and that the average lifespan of a Swedish car is 17 years. We have heard from other sources that most leased cars within Sweden, which tend to be new at the beginning of the leasing period, are at first registered at the leasing company's headquarters, most of which are based in Stockholm, and that this inflates the rate of new vehicle registrations in the region. We also believe that the average lifespan of passenger cars will become somewhat shorter during the coming rapid market shift in propulsion technologies. All together, we estimate the mean lifespan of passenger cars in Stockholm County to 14 years, normally distributed with a standard deviation of four years. Furthermore, we estimate that total EV sales follow the same sales trend as BEVs, shifted two years earlier, and that the remainder of EVs are made up of PHEVs. Among the total transport work by PHEVs, we assume that 70% is performed using electrical energy in 2020, increasing to a ratio of 90% in 2040 because of more ubiquitous charging infrastructure.

Using these parameters, we can forecast the composition of the passenger car fleet in Stockholm County. The trend points towards 90% of passenger car traffic work in the region being electrified in the early 2030s. Given that EVs will likely make up the absolute majority of newly registered passenger cars already within a near future, policy makers wishing to accelerate the transition to an emissions-free fleet should perhaps shift their focus towards policy instruments that incentivize early retirement, or retroactive electric conversion, of ICEVs.

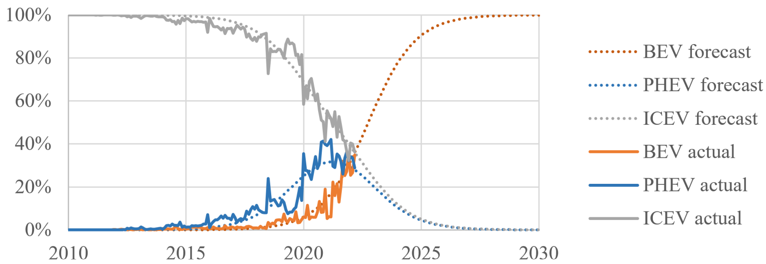

Figure 2: Forecast of PHEV and BEV sales rales ratio.

3.3 Static Charging Infrastructure

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 2022 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 suited to different physical environments where charging is to be installed.

Cable interfaces are not the only solution for static charging. The same conductive or inductive interfaces that enable dynamic charging can also be used for stationary vehicles. Conductive interfaces can transfer 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 in a commercial setting. 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 thorough discussion of the perspectives of users and operators on static charging installed in different types of locations, as well as secondary impact on non-users, can be found in [1].

This research was originally motivated by an interest from Stockholm Municipality to understand what is needed to electrify all passenger car traffic in the inner city. 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 daytime inner-city traffic. Therefore, the scope was expanded to include the county as a whole. The county is the smallest geographic unit for which statistics are available and which we feel comfortable treating as a closed system.

3.3.1 Method to Estimate Density and Quantity of Static Charging Infrastructure

There are significant interaction effects between charging infrastructure sites placed in different locations. A single vehicle can for instance have access to charging at home, at work as well as at a nearby shopping mall and at public fast charging station. The total energy used by a single vehicle in a given time frame is distributed between all sites where the vehicle is charged. Adding more charging infrastructure once a vehicle's charging needs are already satisfied increases system cost, and possibly convenience. Some degree of redundancy is desirable to ensure resilience and flexibility.

The goal of the analysis in this section is to identify the cheapest set of charging infrastructure that is sufficient to deliver the energy consumed by a fully electric population of passenger cars. In addition to minimizing cost, we verify that recommendations minimize the risk of battery depletion for all user segments, and that all residents have access to charging at similar cost. The same assumptions that were used for modelling levelized costs for cars are used to estimate at what state of charge cars will gain access to charging infrastructure, given some placement.

Table 1: Mobility patterns used in the calculation of necessary charging infrastructure density. Percentages indicate the ratio of total regional passenger cars parked at each type of location during night and day.

		Patterns of passenger car use				Leisure time trips to (every n:th day of car use)				
		Night at (default, percent of fleet)	Night in city garage (of days used)	Unused (percent of group, per day)	Commute to (of used cars)	Residential street	Outer city street	Inner city street	City garage, large surface lot	Mall lot
Parking spaces used at night	Single-family home	31%	—	25%	—	1/100	1/14	1/50	1/7	1/7
	Small private garage/lot	17%	—	40%	—	1/100	1/20	1/100	1/14	1/14
	Large lot or garage	17%	—	30%	—	1/100	1/14	1/50	1/7	1/7
Parking spaces used night and day	Residential street	15%	—	55%	3%	1/100	1/14	1/50	1/14	1/14
	Outer city street	7%	1/10	55%	5%	1/100	1/20	1/100	1/7	1/14
	Inner city street	3%	1/10	55%	2%	1/100	1/20	1/100	1/7	1/20
	City garage, large lot	10%	—	55%	25%	1/100	1/14	1/100	1/40	1/20
Parking spaces used during day	Shopping mall lot	—	—	—	—	—	—	—	—	—
	Workplace (small lot)	—	—	—	35%	—	—	—	—	—
	Workplace (large lot)	—	—	—	30%	—	—	—	—	—

Parking behavior within the city and county was approximated using a model that considers the interaction effects between charging infrastructure installed in different locations. This model has ten types of parking (see table 1), between which vehicles travel. The total population of passenger cars is distributed over the different location types (night-time residency) and a frequency of car use is assigned to each group. Regular traffic to work is modelled as a separate distribution of the same location type, with movements between the two location types being sampled independently based on each distribution. 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.

The model has many parameters, many of which are uncertain. With the help of the Traffic Office at Stockholm Municipality, the input parameters were manually calibrated such that intermediate values match known point statistics or domain expertise wherever available. Such statistics include 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. While deviations from reality may be present in terms of absolute counts of parking spaces (and thus charging points), we believe that our estimates of recommended charger densities and resulting occupancy rates are reliable. Levelized charging costs (SEK per unit of energy) are determined primarily by patterns of use, while absolute costs are proportional to the number of parking spaces. Large local deviations from the estimated parking space occupancy rates are known to exist within the city, but data to capture these deviations were not available.

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. We manually 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 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. 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.

3.3.2 Method to Estimate Cost of Static Charging Infrastructure

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. The cost model assumes that all expensive electronics are centralized and that many cheap outlets share a single charge box and grid connection, referred to as a charging site. Further, the model considers that parking spaces are grouped in parking areas of a location type-specific size, with zero or one charging site per area. The number of outlets per charging site is determined by the set size of the parking area and the ratio of parking spaces that are equipped with chargers. The concept of a charging area can be interpreted as the size of an average parking garage or lot, or the maximum walking distance from home for residents who park on the street.

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 distribution system operator (DSO). 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 separate 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. 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.

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) instead result in indirect costs in terms of additional parts in cars. Electricity costs are approximated with the historic average spot prices in the Nordic energy market during daytime and at night, with electricity being significantly cheaper during the night (0.3 vs 0.7 SEK/kWh). Taxes are not based on actual current taxation, but rather scaled to retain the total current tax revenue from the sales of combustion engine fuels.

3.3.3 Scenarios for Static Charging Infrastructure

Table 2 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 1.

Scenarios 1-3 include chargers along city streets, kept sparse by requiring nightly street-parked cars to spend one night every two weeks in a public parking garage[1]. Scenario 4 includes no on-street charging, with the consequence that street-parking residents must rely on weekly charging in public garages and at shopping malls. Weekly or bi-weekly night-time charging in public garages would likely require changes to the rules and fee structures for these garages, but the benefit is improved resiliency for street parked cars, reduced need for on-street chargers, and democratized access to cheaper charging in garages.

All four scenarios include chargers installed at 50% of single-family home parking spaces. This represents a simplification where all single-family homes have one installed charger, but space for two parked cars. No cars are by default dependent on fast charging at energy stations in any of our scenarios. This is further elaborated on in the discussion section.

Although we consider all four scenarios to be viable, we recommend scenario 1. This scenario has a much lower total power demand during the day, which will likely enable more rapid build-out of charging infrastructure than with the other strategies. Scenario 1 also achieves low charging cost and high resilience for all resident groups, while avoiding most problems associated with installing static charging infrastructure at on-street parking places. These problems include raising the cost of other city maintenance, raising the cost of subsurface work, damage to root systems of nearby trees, reduced future flexibility in parking space allocation and obstacles for vision- and mobility-impaired pedestrians. Keeping the charger ratio low at on-street parking spaces means that chargers can be placed only at locations that avoid most of these negative side-effects.

Itemized costs for charging at each type of location are shown in figure 3, based on usage patterns resulting from the infrastructure placement in Scenario 1. Scenario 1 achieves very high utilization of installed charging capacity at all location types, which results in low costs per unit of delivered energy. The usage patterns of the other scenarios lead to other costs, which can grow substantially if the density of charger infrastructure is increased beyond the recommended levels. Electricity costs differ between

[1] Alternatively, no on-street chargers are installed near parking garages, and all charging of street-parked cars near municipal garages takes place there.

Table 2: Four evaluated scenarios with different ratios of charge points at parking spaces in locations of different types. Several performance metrics are included in the bottom half of the table. Street-parking has the highest cost of charging in all scenarios, due to the high opportunity cost of land. Cars parked in single-family homes and in small residential garages during night and at workplaces during the day have the lowest average SoC when they access a charger.

Scenario	Recommended (1)	More street charging (2)	Evenly distributed (3)	Minimal street charging (4)
	Ratio of parking spaces with charging points installed			
Single-family home	50%	50%	50%	50%
Small private garage or lot	40%	40%	30%	35%
Large residential lot or garage	40%	40%	30%	35%
Residential street	15%	25%	10%	15%
Outer city street	10%	25%	10%	0%
Inner city street	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
CAPEX to install all infrastructure (MSEK)	8 406	9 720	10 381	8 848
Levelized cost @ full build-out (MSEK/year)	3 376	4 264	3 776	3 605
Daytime energy	15%	24%	28%	29%
Total MW nighttime	643	575	546	532
Total MW daytime	171	259	336	342
Mean SoC on access (resiliency)	77%	85%	77%	77%
Min SoC on access (resiliency)	64%	67%	63%	63%
Mean SEK/kWh, excl. tax (infra. + energy)	0.9	1.1	1.0	0.9
Max SEK/kWh, excl. tax (low vs. avg is fair)	1.7	3.3	1.7	1.7
Eqv. mean SEK/liter, incl. tax	10.1	11.4	10.7	10.5
Eqv. max SEK/liter, incl. tax	14.6	23.8	14.9	14.6

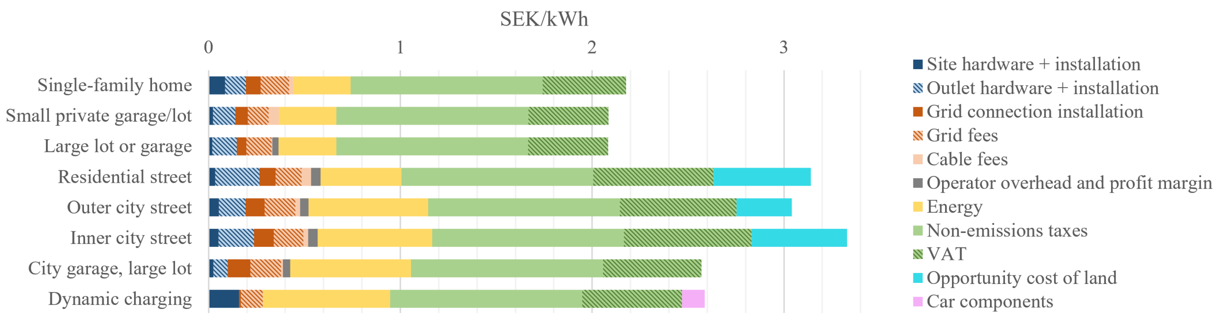

Figure 3: Estimated levelized costs of charging at the different placements recommended in scenario 1.

the locations as different placement results in different ratios of day- and night-time charging. With our assumption of retained tax revenue, the total charging price will be dominated by taxes. Taxes are however excluded from the socio-economic calculations, as they represent a within-system transfer of money, rather than system cost.

The itemized costs for on-street charging in figure 3 contain an opportunity costs of land use. Above charger densities of 10-15%[2] of on-street parking spaces, it becomes cost saving to instead use non-cable (conductive or inductive) charging interfaces that transfer energy from the parking surface (commonly associated with dynamic charging), as in-vehicle costs are independent of charger density.

A few perhaps unintuitive pitfalls have emerged from the modelling work. First, we cannot stress enough the importance of an efficient system for distributing access to chargers. Shifting from random access to demand-driven and fairly distributed access means that around four of five charge points can be removed without risking that any users deplete their batteries. This also greatly raises the amount of energy transferred during an average charging session. With a first come, first serve policy for night-time charger access, residents who arrive home from work later than others are unlikely to ever be able to charge, unless almost all parking spaces offer charging.

[2]Based on assumptions of 7000-14000 SEK/m^2-year, 0.5 m^2 land use per cable outlet, and 470 SEK/car-year for dynamic charging receiver parts. Changes to these assumptions will move the threshold.

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[3]. That charging infrastructure is a prerequisite for EV adoption is represented in our calculations as that total operational charging infrastructure should follow the total ratio of electrified transport work, but shifted one year earlier to have time to influence vehicle buyers. Necessary rates of charging infrastructure deployment and resulting ratios of electrified transport work are shown in figure 4. Two thirds of the charging infrastructure needed for full electrification of the regional passenger car fleet should be operational by 2030. The order in which to install this infrastructure is revisited later in the discussion section.

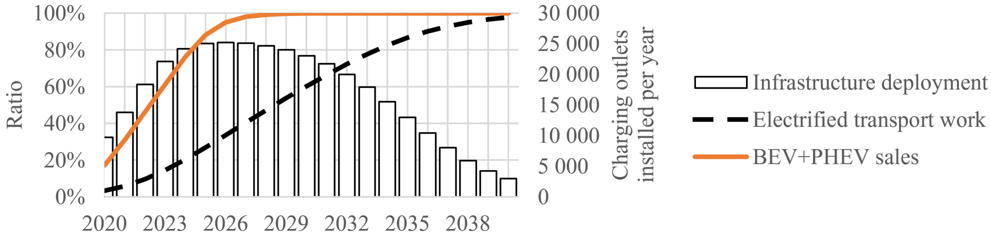

Figure 4: Forecast of fleet composition and rate of charging infrastructure installation.

3.4 Socio-Economic Result Calculation

Our analysis is concluded by estimating the total socio-economic value of electrifying the passenger car fleet within Stockholm County. We do this by bringing together our forecasts of per-passenger car savings from electrification, the ratio of electrified transport work in the regional passenger car fleet, total required charging infrastructure (scenario 1) and resulting infrastructure costs, and the necessary installation rate of charging infrastructure.

Annual and cumulative socio-economic results including and excluding the value of reduced CO_2-emissions are presented in figures 5. Note that the cost of BEV operation is compared to ICEV operation in the same year, not to the cost of ICEV operation in 2020. Levelized infrastructure costs include the initial investment in hardware and grid connections, maintenance, operational fees, operational overhead and opportunity costs of land use. The costs of combustion fuels and electricity are 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, by building out charging infrastructure at a rate below the increase in demand. We estimate this opportunity cost by assuming a faster or slower rate of growth in the ratio of BEVs among newly registered cars (i.e. shifting the dashed black curve in figure 4 along the horizontal

[3]In 2021, 34% of BEVs and 49% of PHEVs sold in Sweden had been exported within five years of initial use. Export rates for ICEVs were around 10% after five years of use and there is no corresponding rate of import of used EVs to Sweden. Other factors than access to charging that can drive EV export are national differences in tax incentives and subsidies, in particular whether these incentivize purchase or operation of zero-emission vehicles.

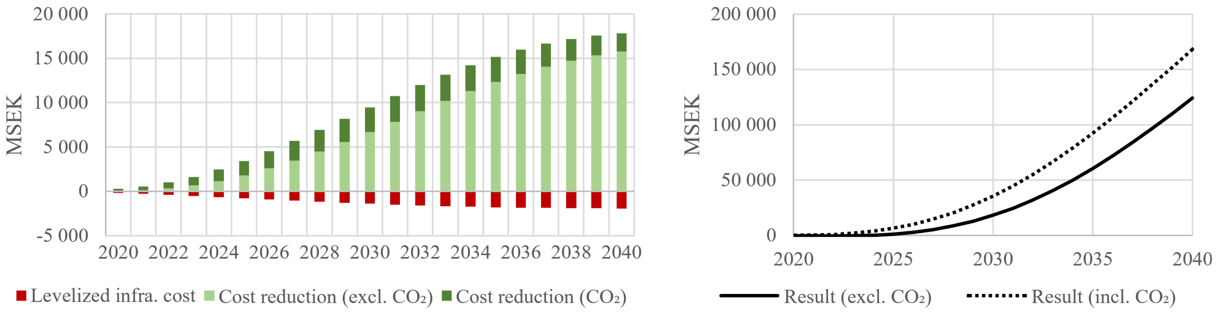

Figure 5: Forecast annual socio-economic costs and savings resulting from electrification of the passenger car fleet in Stockholm County, with charging infrastructure built out according to scenario 1 and vehicle electrification following the forecast in figure 4 (left). Cumulative sum of savings minus costs resulting from electrification of the passenger car fleet in Stockholm County (right).

axis). For Stockholm County, the annual opportunity cost of delay is around 4 billion SEK counting only internalized costs, or 7 billion SEK if the full social cost of carbon is included. Incentives that shorten the lifespan of ICEVs from the assumed 14 years to 10 years also raise this opportunity cost by around 25%. The same incentives would increase the cumulative savings from electrification by 30% until 2030 and by 15% until 2040.

We note that the calculated yearly opportunity cost of delayed infrastructure installation is in the same order of magnitude as the cost of initially building the infrastructure (8 billion SEK for Stockholm County). 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.

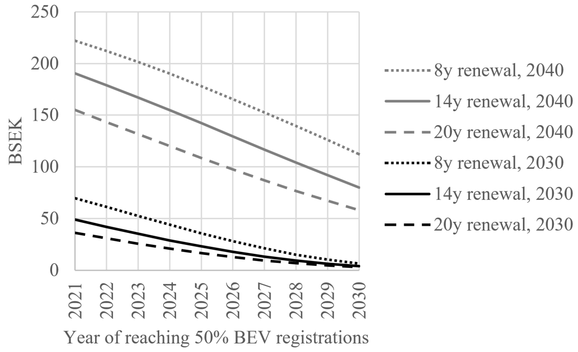

Figure 6: Change in cumulative regional savings (incl. emissions) until 2030 and 2040, from changing the pace of the transition to electric vehicles. Lines indicate different average ICEV lifespans in the fleet.

4 Discussion

4.1 Investment Incentives

Throughout this analysis, it has been clear that users of combustion engine cars do not carry the full socio-economic cost of car use. Both a transition to bio-/electrofuels and a transition to electric vehicles will contribute to internalization of costs, but only electrification will simultaneously lower costs for vehicle owners. A transition to low-emission combustion fuels through regulation is still important, as it strengthens the cost incentive for electrification.

Externalization of emissions costs is a form of subsidy that is greater for ICEVs than BEVs. This subsidy greatly skews the competition in favor of ICEVs[4]. As (only) the public sector can include externalities in its accounting, it also has a greater return on investments that accelerate the shift. Expecting the private sector to carry the initial costs is equivalent to delaying the transition. As internalized cost parity has already been reached in many EV segments, customers who still buy ICEVs are likely to do so due to a (perceived) lack of access to charging infrastructure. Lack of charging infrastructure at the time of initial purchase thus prevents both private and socio-economic savings over the entire lifetime of the vehicle.

4.2 Socio-Economic Distribution of Benefits and Risk

Another type of externalized cost is that of land use along city streets, which is comparable in value to the costs of infrastructure or energy. The cost of land is carried by users of sidewalks, bicycle lanes, parks and other areas that charging poles can infringe on. Non-cable charging interfaces (inductive or conductive) are shown in [1] to reduce overall system costs if more than 10% of the parking spaces are equipped with chargers. Replacing costs of land use with vehicle hardware also helps internalize costs.

Our forecast that future levelized costs of BEV use will be much lower than current costs of ICEV use introduces a dilemma. Should cities allow transportation by passenger car to become cheaper in absolute terms, when this is likely to increase car use, or should all urban car use be made more expensive to compensate, e.g. through parking and congestion charges? Both paths would disproportionately benefit early adopters of EVs, who tend not to be from low-income groups or have special needs.

We do not identify what the best order is to deploy the recommended charging infrastructure, but we can point out several important aspects to consider. The first electric car models to gain significant market share were all premium cars, for reasons explained in [1]. This means that early charging infrastructure demand is greatest in affluent districts within a region, where more residents own newer and more expensive cars. With time, premium model EVs become available in the used car market, and cheaper EV models are introduced. The least affluent population segments, who today own used basic-model ICEVs, are likely to be the last to demand access to EV charging. However, given that ICEV operation is getting more expensive and that replacement of ICEVs with BEVs is expected to offer very substantial reductions in annual household expenses, this is not an attractive transition path from a social perspective, and we argue that the social distribution of benefits from transport electrification need greater attention.

[4] In 2020, the magnitude of fuel subsidies over the lifetime of an ICEV is comparable to a 60% subsidy of new BEVs, even when accounting for CO_2 emissions from battery production.

4.3 Public Fast Charging and 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, in particular when including the opportunity cost of lost time, the cost of increased battery degradation and additional parking space needed to simultaneously charge tens of thousands of cars in locations they do not otherwise intend to visit. 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 enables 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 charging demand before national holidays, and for long-distance travelers passing through a region, if dynamic charging is not available. Energy stations could also work as back-up in case of local residential power outages. Our cost modelling of charging infrastructure highlights the importance of avoidance of power peaks in the economics of charging infrastructure. To avoid power peaks at fast charging stations, it may be very advantageous to co-locate these with bus or truck depots, which have high charger utilization during the times of day that there is least demand for public fast charging.

4.4 Dynamic Charging and Synergies with Commercial Vehicles

While they have not been a focus of this research, 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. Dynamic charging infrastructure (”electric roads”) is accessible to all vehicles[5] that drive on the roads where the infrastructure is installed. As many inner-city roads have the same potential for energy delivery as motorways, urban dynamic charging infrastructure should be considered both for electrifying urban traffic and for integration with a potential future national or European electrified motorway network.

We also note that 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, if the remaining cars are utilized more efficiently through car sharing. Distributing the same traffic over fewer cars would have little effect on the need for charging infrastructure placed according to our recommendations, as the same total energy needs to be supplied every day. However, the less a vehicle stands still, the more difficult it becomes to ensure using static charging that the vehicle will not run out of charge. Dynamic charging becomes more attractive if the overall utilization rate of vehicles increases.

4.5 Regulatory Obstacles

A few regulatory obstacles have emerged in discussions with different stakeholders during the course of this research, which would contribute to cheaper and quicker electrification if removed.

Electricity distribution system operators (DSOs) in Sweden are at present legally prohibited from owning and operating energy storage. Storage technologies are plummeting in cost, and it would be wasteful to not use these for load balancing, peak shaving and other grid management, as an alternative to traditional grid upgrades. As DSO fees are make up a substantial share of operating costs of charging infrastructure, we also advocate for setting these fees dynamically based on current grid congestion. Dynamic grid fees would incentivize placement of charging infrastructure that results in night-time charging and is important that such incentives are put in place before infrastructure is built out.

Reservation of individual parking spaces for individual cars is common in Stockholm and will require installing charging outlets at each parking space if there rules are not changed. Switching to contracts for reserved access to parking rather than individually reserved spaces enables up to an 80% reduction in hardware, installation, and grid-related costs, but an effective method for access distribution, such as a booking system, is required to guarantee charger access for all users. Cost minimization is less important in affluent areas, where users may be more willing to pay a cost premium to have access to private charging infrastructure. City parking garages in Stockholm are at present only available at night to those with long-term contracts. If chargers in parking garages are to complement on-street chargers during night, these rules must either be relaxed, or it must be possible to gain temporary access.

[5] Over-head lines can so far only be used by heavy vehicles.

5 Limitations and Generalizability

Our accounting practices used when calculating socio-economic costs and benefits could be improved in several ways. Vehicle CAPEX is annualized and added to OPEX to get an average cost of vehicle use in each year. This implicitly results in that levelized CAPEX per vehicle changes over the vehicle's lifetime, as only one value is used per year. Interest rates and inflation are not accounted for, and we do not convert future costs to present value. Moreover, neither the size of the car fleet nor the annual driven distance per car are adjusted to match reductions in levelized costs of car use and an expected increase in car sharing. A more advanced method would also jointly optimize car battery pack capacity and charging infrastructure density to minimize overall cost.

This study is a forecast and by necessity relies on assumptions about the future. We believe our sources are credible, but there great uncertainty surrounds many input parameters. 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 CO2 emissions from biofuels, and the social cost of carbon. Fuel prices are particularly volatile and saw an increase by 30-60% during the six-month period preceding the authoring of this paper. Energy prices, while volatile, have a smaller impact on the results. Readers should be aware that Sweden uses a social cost of carbon (7 SEK/kg) above that of most other countries, which affects all calculations involving untaxed CO_2 emissions.

This study uses the same lifetime estimation for BEVs as for ICEVs and the same lifetime for the entire period of analysis. ICEV lifetime is largely based on the lifetime of the combustion engine and driveline, while BEV lifetime is likely to be the lifetime of the battery pack. Battery technology is improving, and it seems reasonable to believe that BEVs manufactured in 2030 will last longer than BEVs manufactured in 2020. This would reduce levelized BEV costs towards the later years of our forecast period below our estimates. Rising costs of ICEV operation may also cause reductions in annual driven distance, which would raise the per-km levelized cost of the vehicle itself.

The challenges faced by Stockholm are not unique and we believe our methodology generalizes well to other regions, but several parameters used will have different values elsewhere. These include energy costs, fuel costs, CO_2 intensity of electricity production, CO_2 valuation, taxes, digging costs, grid substation density, grid subscription fees, car density, annual distance per car, traffic patterns, and ratios of parking types. A spreadsheet containing all calculations and figures will be provided on request to the corresponding author. We recommend spending some time to adjust the parameters to fit the local context before specific conclusions are extrapolated to other regions. Conclusions that should be valid without parameter adjustment are recommended charging infrastructure densities; cost-viability of dynamic charging in large urban areas; that EVs will become cheaper than ICEVs (year of cost parity may differ); that externalization of CO_2 emissions reduces private investment required for transition to EVs; and that very rapid deployment of charging infrastructure is socio-economically beneficial.

6 Conclusion

The analysis in this paper shows that electrification of passenger cars can substantially reduce both socio-economic and private-economic costs [6]. Replacement of fossil fuels with biofuels or electrofuels reduces the socio-economic cost of ICEV operation but raises costs for users. This contributes to an increased ratio of BEVs among new passenger cars in the region, forecast to go from 20% to 80% over a period of less than three years. The recommended rate of installation of new charging infrastructure in the region doubles from 2021 to 2024, to reach a peak level sustained until 2030, to then decline. Sites for chaging should all be in place by 2030, with continued capacity upgrades until 2040. Delaying the regional transition by one year is associated with an opportunity cost comparable to the cost of all regional charging infrastructure, thus achieving high-paced deployment is crucial for cities. The transition can be accelerated by early charging infrastructure deployment and by policy incentivizing early retirement (or retroactive BEV conversion) of combustion engine cars.

Our methodology considers interaction effects between charging infrastructure installed in different locations and we conclude that efficiency and resiliency are both high if only single-family homes, 40% of parking spaces in suburban areas and 10-15% of parking spaces in central urban areas are equipped with charging points. Chargers at places of work and at shopping centers are not recommended, as both raise levelized costs of charging for all, without significantly improving resiliency, as well as substantially

[6] In Stockholm County, the levelized annual cost of operating a BEV is forecast to be 1100, 11000 and 16000 SEK lower than ICEV operation in years 2020, 2030 and 2040, excluding the externalized social cost of CO_2 emissions. Including emissions, the values are 8700, 16000 and 18000 SEK per car-year. Cumulative savings after deducting the cost of new infrastructure from year 2020 for the regional population of 2.5 million inhabitants are expected to be 18 billion SEK by 2030 and 125 billion SEK by 2040, or 35 and 170 billion SEK if the value of emissions is included. The internalized savings go primarily to car owners and total tax revenue for the state is kept unchanged, with the exception of revenue from taxes explicitly tied to CO_2 emissions. The total cost of installing (but not operating) all charging infrastructure in the region is estimated at 8 billion SEK.

raising aggregate power demand during hours of grid congestion. To make sparse charging infrastructure viable, a method for access distribution is required, such as a booking system allowing only one simultaneous reservation per car. This prevents occupation of charging points by vehicles that are unused or almost fully charged on arrival. Night-time charging generally gives lower levelized costs, due to greater utilization of hardware, lower electricity prices and lower grid congestion. If charge points are installed at more than 10-15% of on-street urban parking spaces, charging interfaces that transmit power from the parking surface rather than via cable become cost saving.

We recommend that the public sector takes a very active role in electrification of the transport system, as substantial externalities in the ICEV-dominated system artificially reduce the competitive advantage of BEVs. The transition to EVs is likely inevitable, but early public sector intervention enables greater cumulative savings for both citizens and the state. It is important for a city to identify and adapt to local bottlenecks that counteract the transition. In Stockholm, any good plan for charging infrastructure must be well adapted to high day-time power grid congestion. Other cities may be more hampered by capacity for electricity production during peak demand, outdated zoning laws, or a mismatch between stakeholder incentives and mandates. In addition to direct investment in infrastructure, the public sector can implement policies that incentivize high system efficiency, such as dynamic grid fees, fair pricing of attractive land, and enabling grid-side energy storage for cheap peak shaving. Care should be taken to not subsidize inefficient charging solutions that later prevent more efficient solutions from being built, which could happen if grid capacity or land runs out.

Finally, we wish to highlight dynamic charging (”electric road”) as a viable alternative to cable-based charging interfaces when deploying charging infrastructure for passenger cars in cities. Interested readers will find a comparison of dynamic vs. static charging in the full report [1]. Static and dynamic charging both lead to similar levelized costs of charging, but they have very different pros and cons. Benefits of dynamic charging include shared infrastructure for private and commercial vehicles of all weight classes, the same (low) cost of charging for all road users, smaller viable battery capacities in vehicles, full public sector construction mandate, and no built-in requirement for vehicle downtime. Downsides of dynamic charging include high day-time power draw, less mature technology, lack of standardized charging interfaces, possible lack of public support, and a very large up-front investment.

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Presenter Biography

As a senior researcher in the Mobility and Systems department at RISE (Research Institutes of Sweden), Jakob Rogstadius studies sustainable mobility from a systems perspective. His current primary research interest is optimization and planning of charging infrastructure deployment for private and commercial electric (road) vehicles of all weight classes, at city, regional and national scale. Prior to joining RISE, Jakob worked as a senior data scientist at Swedish truck manufacturer Scania, analyzing mobility patterns from hundreds of thousands of connected heavy vehicles. Jakob holds a Ph.D. in Information Systems.