THE MARKET FOR ELECTRIC VEHICLES – WHAT DO POTENTIAL USERS WANT[1]

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ABSTRACT

This paper investigates some of the factors that influence the potential mass introduction of electric vehicles. The main contribution of the paper is an analysis of how recharging influences the demand. We do this by a joint analysis that includes estimation of a model predicting demand for electric vehicles based upon price, driving range, acceleration, and accessibility to recharging, an in depth analysis of the drivers' need for recharging based on their observed driving patterns found in the National Travel Survey and a GSP based recording of driving behaviour of a sample of drivers in Copenhagen. The final part of the investigation shows that this accessibility to recharging may be one of the most important factors for decision makers to focus on if electric vehicles are expected in larger numbers, but the analysis also shows that this may not be the most important factor when socio-economic assessments are carried out. The socio-economic assessment shows that the revenue impacts for the government as well as the price of the car and the electricity consumption are still key issues in this aspect.

Keywords: Electric Vehicles, Recharging needs, electric car purchase model,

INTRODUCTION

Alternative fuel vehicles and especially electric vehicles are considered important technologies to reduce the CO_2 emissions from transport. The development of electric vehicles is now part of all car producers' strategic plans. At the same time different firms are developing systems to link the electric vehicle's demand for electricity/batteries with the

energy supply systems. One such organisation is Better Place that wants to establish a relation between these two elements by setting up battery swap stations. Several test and demonstration sites are currently being set up or are in some cases already running all over the world. Most of these demonstrations focus on getting electric vehicles on the streets to show to the public that they are working. As part of the demonstrations, different initiatives are introduced. For example making parking slots reserved for and free of charge for electric vehicles. This makes some of the benefits of having an electric vehicle visible and will thus remove some of the perception barriers the conventional car user has against acquiring an electric vehicle.

The barriers against electric vehicles are many; first of all, the price of the vehicles, which is currently relatively high as compared to conventional cars. The operation range is another issue, since the battery capacity is rather limited. Also less tangible barriers exist. For example uncertainties regarding maintenance, resale value, insurance etc.

It is not very well known what the impacts of these barriers are on the potential market introduction of the vehicles. Some studies have tried to measure the potential car buyers' willingness to buy an electric vehicle depending on the properties of the electric cars (Batley et al., 2004, Brownstone et al., 2000, Bunch et al., 1993).

Mass market introduction of electric vehicles is an objective stated at all levels; EU (e.g. through the *Green Car Initiative*), governments, municipalities, car producers, battery suppliers, organisations trying to build a business model in supplying car users with electricity, etc. A key parameter in obtaining the objectives of these various initiatives is to know what the market will be. For this purpose, the properties of the electric vehicles and the supporting infrastructure are central. We also need to know more about the development of these properties such as development in battery capacity, in prices of cars and batteries, in charging infrastructure etc. For the policy planners it is also highly relevant to consider the socioeconomic impacts of different initiatives that may influence the market penetration of the electric vehicles since not all initiatives are equally supportive and the costs may also differ substantially.

Some of the business models for introduction of electric vehicles are linking the electric vehicles and their battery with production of renewable energy such as wind power. This is especially the case in Denmark where the goal is to increase the level of the renewable energy share in the electricity production to 50 per cent by 2020. A problem in connection with wind power production is that it cannot be controlled in the same way as power production from fossil fuels. Hence the match between supply and demand is not balanced, partly because of the very shifting production over time and partly as result of an overproduction at night, and underproduction during day time. The wind power industry thus needs to store energy when production is high and demand is low and reuse it to supply when demand is high. The users of the electric vehicles can be a link between the energy supply industry on one hand and the use of batteries for storage of the excess supply of sustainable energy production on the other hand. This further emphasises the importance of knowing the demand for electric vehicles and the resulting demand for power.

Introduction of electric vehicles is therefore seen as a major initiative in the pursuit of CO_2 reductions. However, there are more aspects involved than just to decide to introduce the cars. And some of these aspects are addressed in this paper.

The first aspect is the car users' demand for electric vehicles and what determines this demand. We estimate a demand model based on a recent stated preference survey of Danish car buyers' choices among alternative and conventional fuel vehicles. This model is combined with similar estimations from the literature to obtain a demand model including central parameters such as the accessibility to recharging. The information about the factors that influence demand for and use of electric vehicles is rather limited. Our analysis is therefore an attempt to make the best use of the limited data.

Recharging is another important aspect for the electric vehicle users because the operating range is limited. We must therefore know to what extent the need for recharging can be met. Without access to recharging in the public domain the electric car can only be used for short daily trips (commuting, shopping and leisure trips in the neighbourhood etc.). On the other hand most trips are of this short distance type so for most users the actual operating range will be adequate. Hence, the second contribution of this paper is to offer a deeper insight into Danish car users' travel patterns to clarify the need for recharging.

The insight provided by this analysis is used to translate investments in public available recharging infrastructure to the electric car users' perception of accessibility into a forecast of the development of the Danish market for electric vehicles. This link is not entirely obvious since electric vehicles can be recharged at private locations (at home, work or other places, where the infrastructure is provided). Accessibility to 'refuelling' is a measure of the extent to which an alternative fuel can be bought at a conventional petrol station. Hence, in the context of electric recharging this traditional measure of accessibility and the level of recharging infrastructure (including fast charging possibilities) need some interpretation. We discuss this particular issue in some detail to find a link between infrastructure investments and accessibility.

With these elements established we can turn to another aspect, namely the costs of introducing the electric vehicles and the potential policies that may support this. This can be used to analyse the issue of welfare costs of electric vehicle introduction into the Danish market. Despite some of the particular aspects of the Danish market, some aspects are relevant beyond Denmark. In Denmark purchase and registration tax on vehicles are high and up to 180 per cent of the purchase price. This means that the price of an electric car, which is exempted from this tax, is similar to that of conventional cars. From this perspective the potential for mass introduction of electric vehicles is relatively promising in Denmark. However, it is not without costs to do this. We summarise how the socio-economic costs and benefits add up to find the costs of reducing CO_2 emissions through introduction of electric vehicles. The calculations provide a basis for comparing electric vehicles as a relevant measure to deal with the CO_2 reduction targets with other instruments.

Our contributions will be covered in the following sections. The next section describes the estimated demand model, which is mixed from new estimated effects and results obtained in other earlier models from the literature. The section is followed by the analysis of the users' demand for recharging and by the analysis of the potential market introduction and the social welfare costs of doing this. We end the paper with a discussion of the main findings in relation to each other and in relation to the international market potential for electric vehicles. We further point out gaps in the existing knowledge.

A DISCRETE CHOICE MODEL FOR ELECTRIC VEHICLE DEMAND

A model to assess the influence of attributes relevant for the purchase of electric vehicles and capable of analysing market shares is set up. As a model framework we use discrete choice models based on random utility theory, more specifically a multinomial logit (MNL) model, see Ben-Akiva and Lerman (1985). In this section, we first discuss the data used for the estimation, then we present the applied specification and the estimation, and finally we present the model used for policy analysis.

Data

To develop our demand model for electric vehicles we rely on a Stated Preference (SP) study conducted from August 2007 to July 2008, see Mabit (2009) for further description. The study compares several alternative fuel vehicles to the existing petrol and diesel alternatives. Here we only rely on the sub dataset where conventional vehicles are compared to electric battery vehicles in binary stated choice experiments.

The stated choice experiments were created using a pivoting design where the attributes were pivoted around values obtained from a recent vehicle purchase of the respondent, denoted as the reference vehicle. The experiment had two monetary attributes purchase price and annual costs both in DKK[2]. The annual costs included maintenance, fuel expenses (based on intended driving), and annual taxes. The non-monetary attributes included acceleration time in seconds to reach 100 km/h, operating range in km, and a service dummy. Pollution levels were not varied but the respondents were informed that a conventional alternative would pollute like their reference vehicle while electric vehicles had no pollution.

In the literature, SP studies are commonly based on random samples from the entire population or samples with individuals intending to purchase a vehicle. Instead we contacted a sample representative of the population of new-car buyers. As it is this population that may actually change the composition of fuel types within the car stock, this seems more appropriate. The survey was carried out using the internet. The average response rate

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[2] 1 Euro = 7.5 DKK.

across months was 28 per cent. The final sample has 1348 individuals each making 4 choices giving a total of 5392 observations.

Estimation

We specify an MNL model. For individual *n* we assume that the utility of alternative *j* is given by

$$U_j = \alpha_j + \beta_{price}x_{price,jn} + \beta_{anc}x_{anc,jn} + \beta_{acc}x_{acc,jn} + \beta_{range}x_{range,jn} + \beta_{ser}x_{ser,jn} + \varepsilon_{jn}$$

where α, β are parameters to be estimated, x_{price} is the purchase price, x_{anc} is the annual cost, x_{acc} is the acceleration time, x_{range} is the operation range, x_{ser} is the service dummy, and ε_{jn} is an error term assumed to follow a Gumbel distribution IID across individuals and alternatives. We set the alternative-specific constant for conventional vehicles equal to zero for identification. The model has 6 estimated parameters. The model is estimated in Biogeme using maximum likelihood estimation. The final log-likelihood is -3096.8 giving a $\rho^2 = 0.17$. The parameter estimates are presented in Table 1. T tests are calculated using robust standard error estimates.

Table 1. Parameters estimates

Parametres	Units	Estimate	T test
Purchase price	100,000 DKK	-1.34	-23.74
Annual costs	10,000 DKK	-0.643	-7.93
Acceleration	Seconds	-0.049	-3.06
Range	Km	0.0017	10.74
Service (EV)	dummy	0.323	5.28
Constant (EV)	dummy	0.286	6.69

The estimates have the expected signs and are all significant. Acceleration time and monetary attributes are valued negatively while range and service are valued positively. Service only enters as variable in the utility for electric vehicles. The uncertainty variable may thus be interpreted as uncertainty among respondents concerning possible unexpected maintenance related to electric vehicles.

Final model

The final model parameters to be used in the policy analysis are found in Table 2.

Table 2. Model parameters

Parametres	Units	Source	Estimate
Purchase price	1000 DKK	DTU estimation 2009	-0.0134
Running costs	oere/km	DTU estimation 2009	-0.0116
Acceleration	Seconds	DTU estimation 2009	-0.0488
Fuel availability	% of fuel stations	Batley et al. 2004 (UK)	0.044
Range	Km	DTU estimation 2009	0.0017

Constant for EVs	Assumption	0

The price, acceleration, and range parameters are taken directly from our estimation above. The running cost parameter is calculated by using the estimated coefficient for annual cost above and using an assumption that the average car drives 18,000 km in a year. The fuel availability parameter is based on results found by Batley et al (2004). Availability is in their analysis understood as the share of the conventional fuel stations that have possibilities for buying alternative fuels. Here this would correspond to the possibility for recharging. However, recharging can happen at many different locations and do not necessarily have to be done at a fuel station. On the other hand recharging is needed more often than refuelling of conventional cars and charging will on average take more time. The accessibility variable is not considering what type of recharging is done – normal charging or fast charging, but simply that recharging is possible. We discuss this relation further in the subsequent sections

Batley et al. (2004) report a direct fuel availability elasticity around 0.43. Given the remaining parameters and our attributes used in the base 2010 scenario, we calibrate the fuel availability parameter such that the elasticity of demand for electric vehicles is 0.43 with respect to fuel availability. A final parameter is the constant for electric vehicles. This constant has been estimated in the literature as both positive and negative. But in general it is positive if a pollution attribute is not included in the model. Here we are conservative and set it equal to zero. We have not included the service parameter in the table. For our use of the model for predictions of future market shares it seems reasonable to assume a common service across fuel types. Therefore the variable is set to zero and the parameter becomes irrelevant.

The demand model here is estimated based on some indirect assumptions. First of all it is assumed that the electric vehicles are available, that they in all other aspects than those presented on the SP study are similar to conventional vehicles. This implies for example that the model and makes are numerous. These non included aspects are in principle included in the constant. However, it is not entirely certain that this is adequate, especially when the model is used for predictions of future market shares. Another issue is that the model is estimated linearly, which implies that the impact on demand is independent of scale. Hence, the impact of additional accessibility is the same independent of how many recharging possibilities there exists. A final consideration is the transfer of the fuel availability coefficient. We add a fuel availability parameter from another study. To do so we assume that fuel availability, which is an infrastructure attribute, is uncorrelated with the other attributes, which are monetary and technology attributes. The best would of course have been if availability had been part of our SP study. As it is not we rely on this practical approach.

RECHARGING – THE CENTRAL PARAMETER

The choice model indicates that accessibility to recharging is a key parameter in the choice of electric vehicles. But how much charging infrastructure is needed? In this chapter we will uncover the basic need for charging which is directly related to the travel behaviour by studying the driving patterns of conventional cars. For the potential electric vehicle owner it is

a precondition for purchasing an electric vehicle that the new car is expected to cover the travel behaviour of the family. Therefore it is relevant to analyse the travel behaviour of conventional cars to reveal the expected needs from the car purchaser's point of view.

If a family has bought an electric vehicle then the actual driving and charging pattern might be different from the use based on expectations derived from the pattern of a conventional car, because it is much different to have a car which can be charged at home, at working places etc. than having a car, which can only be refilled at a fuel station. For this purpose an analysis of the real travel pattern of electric vehicles would be more relevant. However, such data does not exist at the moment due to the few electric vehicles in the car stock.

Available data

In Denmark two different datasets are relevant for the analyses of travel patterns of passenger cars. The Danish National Travel Survey (NTS, 2002-2003, 2006-2008) which is interview based data about travel behaviour of the population, and AKTA data which is GPS-based data following the cars (Nielsen and Sørensen, 2008). None of these are ideal for the purpose, but together they can illustrate the travel pattern to a certain degree. The advantages and disadvantages of the two datasets are:

- The NTS data are interview data with detailed travel information collected daily over many years from a representative sample of the population. A problem with these data is that the information follows the respondent's behaviour and not the travel pattern of the car, because the Danish NTS opposite to some other countries is collected based on individuals and not on households. This means that it is impossible to know how much the car is driven by others than the respondent.
- The AKTA data were collected in 2001-2003 as part of a road pricing trial. A total of 360 cars was followed by GPS from 14 to 100 days in 2001-2003. The data can be used for the analyses of the actual driving patterns of the cars during a week and partly also during a month. The detailed information about the trips is, apart from the exact geographical positioning, very modest. The most important disadvantage is, however, that the data only regard cars belonging to families with one car, families living in Greater Copenhagen, and only families attached to the labour market. Hence, the dataset is not representative. However, as the information is unique we still use it as an indicator of the actual charging needs.

Technology of electric vehicles and charging facilities

Whether an electric vehicle can fulfil the need for transport depends on the range of the battery. At the moment most electric vehicles only have capacity for driving 60-80 kilometres before they need to be charged. However, the capacity will be improved and the driving range according to the car manufacturers will be 120-180 km when the new generation of electric vehicles with Li-Ion batteries are mass produced in the next few years. These driving ranges are only obtained if the cars are driving at a maximum of 80 km/hour, though. As

soon as the speed is increased to 100 km/hour or more it will run out of electricity after a much shorter distance. It is therefore decided to elucidate the possibilities of different battery capacities with driving ranges from 80 km to 200 km.

Even though the cars have these capacities, the drivers will not discharge the battery completely, as they will of course not risk running out of power. In the calculations it is therefore assumed that the battery will need to be charged when 20 km of the travel range is left. When using NTS data it is furthermore assumed that all cars can start the day with a fully charged battery, i.e. they are charged during the night.

Two different kinds of charging facilities are taken into account in the analyses, traditional plugs and lines with 230 Volt which facilitate 10 Ampere as maximum, and fast charging stations. The expected new type of charging poles with 400 Volt and 16 Ampere are not included in the analyses. The fast charging facilities can both involve charging facilities and battery swapping facilities. Which of the two will be used depends on the type of the electric vehicle but for the analyses in this chapter fast charging is used synonymous with battery swapping and only means that charging can be overcome fast. It is a prerequisite that fast charging will only be used when the driver is at a trip longer than the driving range of the car.

Charging away from home

According to the NTS data and based on the above prerequisites, 87 per cent of the population holding a driving licence does not travel so far by car on a given day that they have to charge during the day, if the car has a travel range of 80 Km. If the battery holds a travel range of 200 km, only 2 per cent of the drivers will travel distances during the day that are longer than allowed by the battery capacity.

The above statement is based on NTS data that only reveals information about the driver's travel length. In a family owning only one car, but with 2 or more family members holding a driving licence who have to share the car, one persons' driving activity cannot be assumed to be equivalent to the driving performed by the car.

Table 3 *Percentage of cars* that are not driving on a particular day, as well as percentage of cars that is actually driving on a particular day but need not to be charged. Shown for different driving ranges and different number of cars and driving licences in the family.

	1 car	**2 cars**	*3 or 4 cars*	**2 cars**	**3 or more cars**
	1 driving licence	**2 driving licences**	**Same no of licences**	**1 driving licence**	**Fewer driving licences**
Car not driving	38 %	29 %	26 %		
Percentage that only needs to charge at home at: 80 km	79 %	70 %	74 %	71 %	70 %

100 km	86 %	79 %	83 %	79 %	79 %
120 km	90 %	85 %	89 %	84 %	87 %
160 km	94 %	92 %	94 %	92 %	93 %
200 km	96 %	95 %	96 %	94 %	96 %
Percentage that drives longer	4 %	5 %	4 %	6 %	4 %

In Table 3 the driving performed by the car is elucidated. In families with 1 car and only one driving licence, the car driving is considered to be more or less equivalent to the driving performed by the car. This group makes up 17 per cent of the driving licence holders. As regards single persons, 79 per cent of those using the car drives less than 60 km on the particular day and will therefore not need to charge during the day, if the person in question has a car with a driving range of 80 km. If the driving range of the car is 160 km, 94 per cent of the people living alone could manage without having to charge the car during the day on a given day. But maybe they will have to charge their car away from home at another day.

If a family with 2 driving licences has 2 cars, it can be assumed that, on average, the cars have the same driving pattern as independent single persons. The group makes up 16 per cent of driving licence holders. On average, only 70 per cent of those who are driving the actual day can manage without charging the car during the day, if the car has a battery capacity of 80 km. If the capacity is 160 km, 92 per cent can manage without charging. Therefore, families with 2 cars often travel long distances compared to people living alone and couples where only one of the partners has a driving licence.

Families with 3 or more cars only makes up 1 per cent of the driving licence holders and 2 per cent have more cars than driving licences. None of these groups are relevant to take into account.

Table 4 *Percentage of respondents* that is not driving on the particular day and the share driving shorter than different distances. In the last column a calculated *percentage of respondents* that are not driving on the particular day is shown

	1 car 2 driving licences	1 car 3 or more driving licences		1 car 2 driving licences
Person not driving	46%	49%	Car not driving	21 %
Percentage of drivers who drives less than: 60 km 80 km 100 km 140 km 180 km	 78 % 85% 89% 94% 96%	 78 % 85% 90% 95% 97%	Percentage of driving cars only needing to charge at home at: 80 km 100 km 120 km 160 km 200 km	 65 % 75 % 81 % 90 % 93 %
Percentage that drives longer	4%	3%	Percentage that drives longer	7 %

For families with 1 car and 2 driving licences, which make up 45 per cent of all respondents, the average travel length distribution for each of the family members holding a driving licence is known (cf. Table 4). 78 per cent of these drives less than 60 km and 94 per cent drives less than 140 km, in case they are driving a car the actual day. So their mean length distribution in car corresponds fairly well to that of people living alone. But the share of people not driving a car at all is much bigger. And the more people who have to share the car, the more of them will not get the opportunity to drive the car on the particular day, 46 per cent in case of 2 driving licences and 49 per cent in case of several driving licences, respectively (cf.Table 4). When a person is the only one to use the car, it is only 38 per cent that does not use that opportunity on a given day (cf. Table 3)

To get an idea of how much the car is used and thereby when it needs charging, it is assumed that the two persons in a family with 2 driving licences use the same car but independently of each other. The result of this calculation is shown in Table 4. In that case it is only 21 per cent of the cars that are not driving. And it is only 65 per cent of those cars which are driving at the actual day that do not need to charge during the day, if the car has a driving range of 80 km. If the car has a driving range of 160 km, 10 per cent would have to charge the car during the day. Exactly the same distribution of distances is found when a man and woman in a one-car household are combined in a similar calculation.

Based on these numbers it is not possible to assess how much the cars drive when studied over a longer period. To assess this variation in more details, the AKTA data is analysed. They cannot be directly compared with the above-mentioned average numbers for the entire population, because they only comprise one car families in the working age population and only cars in the Copenhagen area.

Part of the cars comprised by the AKTA data was followed during 13 days and nights, whereas others have been followed for a longer period. In Figure 1 it is therefore shown how many days the car could not avoid charging during the day in a 13 days' period dependent on the number of people who has to share it (one or two/several). It appears that very few cars can avoid charging during the day one or several times during the 2 weeks (13 days). If the car has a driving range of 80 km, only 3 per cent of the owners in families with two ore more driving licences can avoid charging and 11 alone of the people living alone. With this low capacity a small part of the potential car owners would have to charge away from home at least every second day.

Even with a driving range of 160 km, it is only one third of the families with several driving licences and a little less than half of the people living alone that can avoid charging during the day during a 2 weeks' period. So it is of no use that 12 per cent of the families attached to the labour market and holding 2 driving licences and 7 per cent of the people living alone according to analyses with the NTS can manage without charging on a given day with this driving range. Over a period only few families will manage without charging outside home.
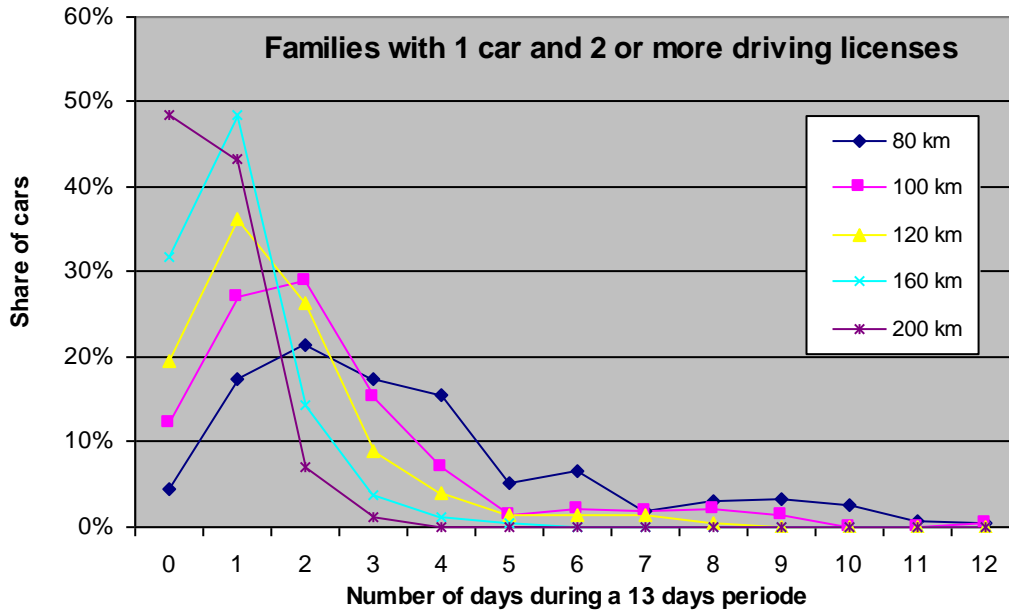
Figure 1 Percentage of cars that has to be charged away from home 0, 1, 2 etc. days during a period of 13 days. Represents a family with one car and 2 or more driving licences in Greater Copenhagen. Akta data

Need for fast charging

When charging poles are available at all workplaces and in city centres, shopping centres etc., most of the drivers that need to charge away from home in their daily activities could manage with these charging possibilities.
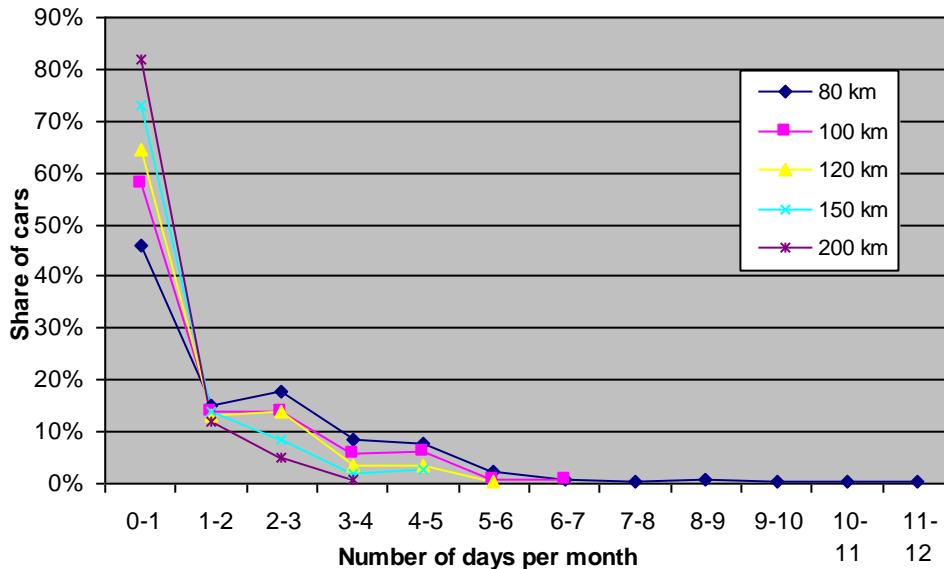

Figure 2 Percentage of cars that within a month needs to perform fast charging during the day, on only a few or several days. Source: Akta data

However, sometimes the car owner will travel longer distances and therefore need fast charging on the trip. According to the analyses of the AKTA data, less than half of the drivers

can avoid fast charging during a month, if their cars have a driving range of 80 km, cf. Figure 2. If the range however, is 150 km it is almost one third that can avoid fast charging during a month. Approximately 15 per cent of the cars must perform fast charging at a couple of days and approximately 20 per cent once a week if they only have a range of 80 km. In case of a driving range of 150 km or more, a maximum of 8 per cent will have to perform fast charging approximately once a week.

Furthermore it will often be necessary to charge several times during the day, once the need for fast charging has been established, cf. Table 5. If the capacity is 80 km, it is less than half of the cars that can do with charging only once, and 20 per cent must charge more than 3 times. And even in case of a capacity of 150 km, half of the cars must charge more than once the actual day.

Table 5 Average number of fast charging operations per day, Source: TU data

	80 km	100 km	120 km	150 km	200 km
Family with 2 cars and 2 driving licences	1.82	1.70	1.54	1.38	1.26

THE MARKET POTENTIAL

From the two previous sections we have learned that recharging is an important aspect in the potential electric vehicle buyers' choice and that recharging only to some extent cannot be done at the location where the owner lives. Hence, there is a need to invest in public charging facilities either by private entrepreneurs, by the public or in a combination. However, the decision to do so cannot be made without judging such initiatives in comparison with other initiatives to target CO_2 reductions (in the transport sector).

In the present section we will discus the relationship between charging infrastructure and the variable *accessibility*, which is the variable, where recharging possibilities influence the user demand. The investments may be very large and it is thus also relevant to investigate how this influences the socio-economic performance of the electric vehicles. We therefore also discuss some examples of such calculations to complement the market potential investigations.

The decision of introducing policies and initiatives to support the introduction of electric vehicles is in Denmark partly based on the welfare economic impacts in a similar way as other transport political decisions are based on the social welfare impacts. The methodology for doing this follows the HEATCO (2006) guidelines with a few changes. The similar approach has been outlined in Ministry for Transport (2003).

The initiatives and thus also the market potential analysis, have long term impacts. We therefore need knowledge about how impacts of an initiative develop over time. We use the demand model described above to do this and use a set of values for the included variables as outlined in the Annex. The uncertainty about many of these variables is naturally large since only a limited number of electric vehicles are introduced in the market and the expectations about developments in battery capacity, battery price and the price of the

electric vehicles. The values we have used here are averaged over prices of existing electric vehicles and the price of new electric vehicles as indicated by the producers.. Most of the figures have not yet been documented in international literature, but they are described in Trafikstyrelsen (2010). However, as we shall see most of the values do not play very significant roles in the forecast as already indicated above.

A central variable is the price on the electric vehicle. We apply a price before taxes and VAT of an average electric car without batteries of 96,000 DKK. This can be compared to an average of 81,000 DKK for an average conventional car. The prices of these cars are assumed not to change. The price of the battery is set to 50,000 DKK in 2010 falling to 30,000 DKK in 2020. The total price of an electric vehicle is 206,000 DKK and the used price for a conventional car is 213,000 DKK.

We also have made general assumptions about the future car stock and used current Danish fuel taxes as well as fuel prices. These are also shown in the annex.

What we do need to establish is the relationship between charging infrastructure and the vehicle users' perception of accessibility to recharging/refuelling. There is no direct way of measuring this relationship and the measure of accessibility in relation to recharging is thus a matter of interpretation. In (Batley et al, 2004) accessibility is referred to as the share of conventional fuel stations that have an alternative fuel for sale as explained in the previous section. Here this would correspond to the possibility for recharging. However, recharging can happen at many different locations and do not necessarily have to be done at a fuel station. On the other hand recharging is needed more often than refuelling of conventional cars and charging will on average take more time.

A basic assumption in our analysis is that a private possibility of recharging is bought with the car. Besides this additional charging facilities are denoted public recharging and it is the extent of this that can be influenced politically.

Generally we interpret the relationship so that there is an upper limit to accessibility for electric vehicles, which we have set to 90 per cent. In the demand model we let accessibility increase linearly from 5 per cent in 2010 to different levels of accessibility with a maximum of 90 per cent in 2020.

In Figure 3 we show the development in the electric car fleet in Denmark (total amount of cars is 2.5 million) under different alternative 'policies'. The policies that are shown are summarised in Table 6. The policies that are referred to are 1) the extent of infrastructure investments (private or public), 2) the timing/speed of the investments and 3) using tax exemption for electric vehicles. This third policy is formulated such that the current Danish tax exemption until 2012 will be prolonged.

Table 6. Analysed alternatives

|	Purchase tax / Tax exemption	Investment in infrastructure starts	Accessibility in 2020	Electric vehicles in 2020
Basis	Exemption until 2012	Early at moderate level	High	235,928
Basis and tax exemption	Exemption all years	Early at moderate level	High	282,919
Head start	Exemption until 2012	Large initial investment in 2010 and then gradual increase	High	298,831
Slow investment, low max accessibility	Exemption all years	No initial investment and moderate investments after 5 years	Moderate	58,392
Reduced max accessibility	Exemption all years	Early at moderate level	Moderate	68,323
Slow investment	Exemption all years	Real start delayed 5 years but will from then happen at high speed	High	156,586
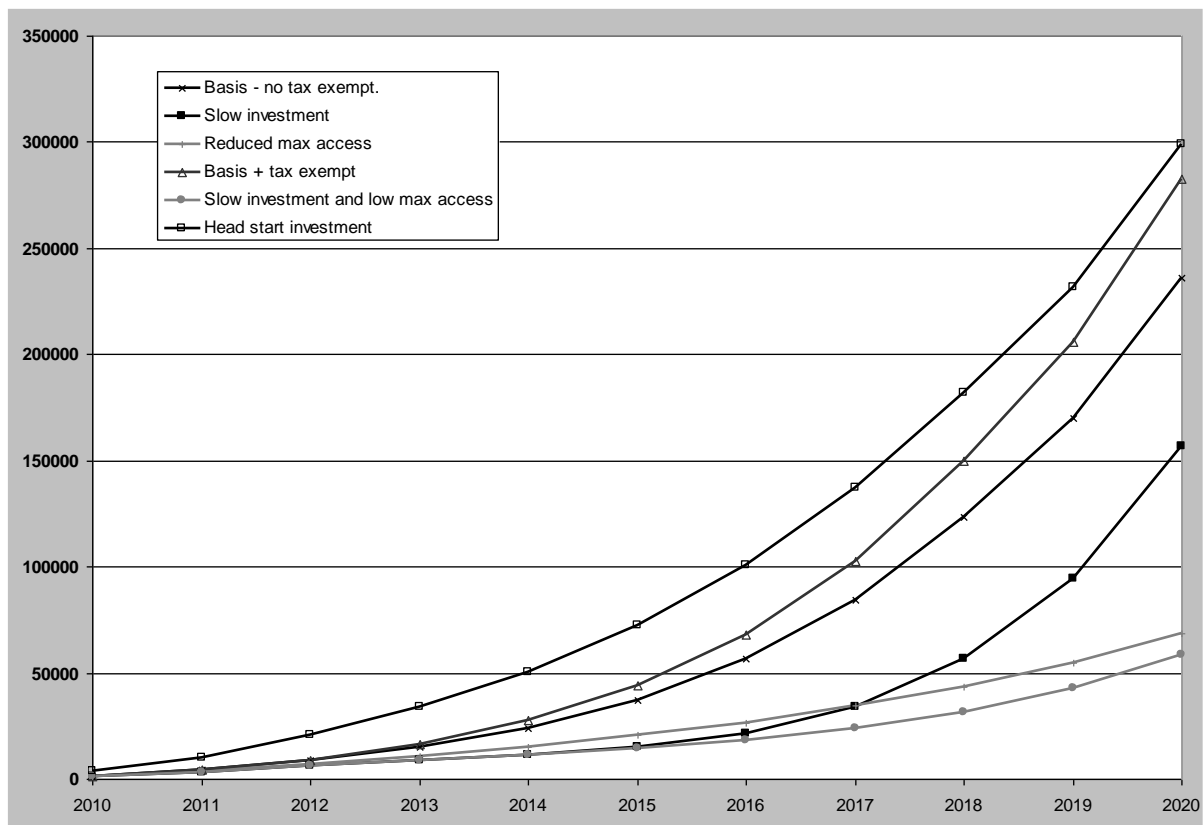
Figure 3. The calculated market for electric vehicles under different alternatives.

To further illustrate the importance of accessibility and that it is highly relevant to establish a credible link between recharging infrastructure investments and the accessibility variable in the demand model, we have included a 'policy' where the investment only leads to half the accessibility of the other analysed developments.

Figure 3 reveals a number of interesting results. There are significant differences in the numbers of electric vehicles in the different alternative from a minimum of 58,000 vehicles in 2020, when investments in charging infrastructure are slow at the initial level and the final level of accessibility achieved is also low; to a maximum of 299,000 electric cars, when a huge initial investments in recharging infrastructure is done already in 2010 and the purchase tax is abolished after 2012 and final accessibility is high.

The final level of accessibility is central for obtaining a high number of electric vehicles. When the final accessibility is kept at 50 per cent then the anticipated number of electric cars will be less than 70,000, however if the investment in recharging infrastructure is delayed, then this also have a large impact on the number of electric cars (157,000 compared to the 236,000 that would be the result with a steady increase in the investments already from 2010). In this particular calculation, we do not assume that a delay in investments in recharging infrastructure prevents achieving a full accessibility in 2020.

The effect of prolongation of the purchase tax exemption of electric vehicles after 2012, which is the last year the current exemption is applicable[3], does not appear to have a large impact on the demand for electric vehicles. The difference in number of electric cars in 2020 is less than 50,000. This is due to the relatively limited amount that this purchase tax is expected to be for the energy efficient electric vehicles (it is anticipated that the tax will be 20,000 DKK). In 2007 the Danish government changed the purchase tax on cars such that a reduction was given to energy efficient cars with a large km/l value. This also accrues to electric cars. However, if electric cars use wind power electricity then the km/l value for electric cars is in principle infinite and no tax should be paid. In practise the level of 20,000 DKK is the level currently accepted as the level to use – it is still uncertain what the value will be, though.

The potential effect of investing and establishing a good infrastructure will possibly have a much larger effect on the demand. This is because there is room for a much larger change compared to the possibilities with the economic instruments. In relation to this we can also mention that the tax on electricity is an even smaller part of the price of electricity and the possibilities for applying this as an instrument will have an even smaller impact on demand.

From the results illustrated we also find that the infrastructure should be installed relatively quickly due to the large impact it has on demand. A delay in the investment will lead to a small demand in the first years until the infrastructure is installed, but due to the accumulation of electric vehicles, the share of electric vehicles will furthermore be smaller in 2020 and it will take longer before the market share is at a level, where it will be relevant to use electric vehicle batteries for power storage in an intelligent charging set up.

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[3] The Danish parliament is currently discussing whether the exemption should be prolonged.

The welfare economic impacts of policies aiming to increase the market share of electric vehicles will depend on these levels of the infrastructure through their impacts on the number of electric cars boith through the impact on demand and though the investments that needs to be made.

Accessibility and recharging facilities

To establish a link between the number of available recharging spots and accessibility, we have to analyse both the need for fast charging stations and for access to charging poles. The analyses are based on the NTS for 2006-2008.

All electric vehicles need to have a charging possibility at home. 75 per cent of the actual car park is owned by families in single family houses, 10 per cent is owned by families in flats in the dense part of the cities and 15 per cent in flats in suburbs and smaller towns. Out of the 10 per cent in flats in the dense part of the cities we asses that 1-2 per cent points have access to car parking in the backyards and 8-9 per cent points need to park in the streets and other public parking spaces. If the electric vehicle stock is distributed over housing types as the actual stock 75 per cent of the charging facilities for the residential charging has to be established by the car owners at their own houses, 17 per cent at parking areas at residential stock houses and 8-9 per cent in public parking areas.

61 per cent of the actual car park is owned by respondents who are active in the labour market. Of these 13 per cent points have a commuting destination in the central areas of the cities and 33 per cent points in the suburbs and 15 percent points in small towns and countryside.

Some of the work places in the central areas of the cities are located in the same areas as the private residences so that the employees are using parking spaces which are free in daytime. We assess that a little less than half of the residential parking spaces – 3 per cent point - is left in daytime so it can be reused for day-long parking. Furthermore some of the companies have private parking areas so the employees will not need to park in the streets. We asses this to be another 3 per cent points.

If everybody needs a charging pole at the working place it is assessed that 10 per cent of the electric vehicle stock needs a charging pole as street parking and 3 percent at private parking areas in the central cities and 33 per cent at the companies' private parking areas in the suburbs. At least 15 per cent will have access to charging at private houses at work places without an official parking area where they can use a normal plug for charging (at farms, small firms with few employees etc.)

If the electric cars also need to be charged when the owner is shopping or is going to recreational activities in the cities charging poles have to be established at such areas too. Saturday is the day with most shopping traffic and the maximum parking capacity in use. If charging poles are available at Saturdays the need for all days is covered. The population is

driving 0.25 trips per person by car as driver to shopping and the like activities on Saturdays. Furthermore 0.05 trips per person go for places of entertainment, restaurants etc. This means that 25 per cent of the cars are on a shopping trip in average and 5 per cent on other kind of trips to the city centre, most in the evenings. 8 per cent points of the trips have a destination in the central area of the cities, 14 per cent points in the suburbs and 3 per cent points in villages and rural districts.

Table 7. Summary of need for charging poles

	Street parking	Shopping centre parking	Residential stocks	Company employees parking	Total	Private houses
Residence	8 %		17 %			75 %
Maximum need						
Working places	7 %			36 %		15 %
Shopping, recreation	5 %	10 %				
Maximum needs, total	20 %	10 %	17 %	36 %	83 %	
Minimum need						
Work, shopping	4 %	1 %		12 %		
Minimum need, total	12 %	1 %	17 %	12 %	42 %	

Not all the cars are parking at the same time and some of the parking space for employees in the city centres can be reused for shopping at Saturdays. On the other hand parking for shopping is also needed in the city centres on working days apart from the employees' parking. This is in fact 0.6 trips per person but spread out over a longer period. To conclude we asses that 5 per cent of the electric cars should have a parking space in the city centre when all needs have to be met. At the shopping centres in the suburbs reuse of the parking areas from employees is not possible to the same degree. However, some of the shopping trips go for small shops with short time in the shop where it is not possible to charge. The same is the case with most of the shopping trips to the villages and countryside. Therefore we asses that only 10 per cent of the electric vehicles need a charging pole in the shopping areas.

On top of these charging possibilities we will add 4 per cent for other purposes as sports areas and recreational areas outside the cities. In all the maximum need for charging poles outside private residences and small firms will cover 87 per cent of the electric car stock at the actual year. These charging poles should charge with 16 Amp.

However, as described in the former section only few electric vehicles need to charge outside home at a given day. If all electric vehicles only have a travelling range of 80 km 28 per cent of the cars in families with one car and more driving licenses will need to charge outside home on a given day. In the rest of the families maximum 20 per cent need to charge. Each group is about half of the stock so the minimum level for charging outside home will be no more than 25 per cent of the maximum need. Most of the charging poles

have to be at the working places. The total minimum need will be about 43 per cent or half of the maximum need.

The closer to the minimum level the number of poles is the higher is the risk that no pole is free when a car need to be charged. This will also be the case at working places if they only have charging facilities for those cars that always need to charge. At some days others will need some extra charging because of a detour or a business trip.

There is a need for fast charging as the analysis above indicated. Due to safety issues and technical constraints regarding this, fast charging can only be done at manned recharge stations. The number of fast charging stations must at least be at the level of conventional fuel stations to make long trips possible. Since the operation range is much shorter than conventional car's it could be argued that an even finer level of spatial coverage is needed. However, it is less than 20 per cent of the cars that requires fast charging more than one or two times per month. Demand for fast charging is thus relatively limited, but when the need is present, it is crucial that the possibility is within a reasonable distance.

Welfare economic impacts

The socioeconomic welfare calculations we have done follow the general Cost-Benefit analysis recommendations put forward by the European project HEATCO (2006) and adapted to a Danish context (described in Ministry for Transport, 2003). This methodology prescribes both the methodological approach and have a catalogue of unit prices to be used for these analyses (Ministry for Transport, 2009).

What is basically happening when a conventional car is substituted by an electric car is that the user pays a little less for the car and therefore receives an increase in consumers' surplus; the government faces a loss in revenue from purchase taxes. Not only the loss due to the policy of exempting electric cars from purchase taxes, but also the revenue from purchase taxes on conventional cars. In addition to this there is also a shift in fuel consumption from a fuel with relatively high taxes to a fuel with relatively lower taxes. These tax revenue effects are the main welfare economic effects of introducing electric vehicles. It is an effect that will arise independently from which policy is used to ensure this introduction.

The other effects of the different policies are the extent of investments in charging infrastructure. This investment can be made both by private entrepreneurs such as Better Place or by the government. The difference between these two investors is that the government must raise the finances by increasing taxes elsewhere and this induces an extra cost known as the marginal cost of public funds (MCPF). MCPF is the cost of collecting taxes (on average).

On the benefit side we get a reduction in CO_2 emissions and other emissions. We further get a small reduction in noise.

In order to calculate the shadow price of a reduction of one ton CO_2 the costs and benefits from the different policies (tax exemption and investment in charging infrastructure) are calculated. The shadow price is found as the relation between the net benefits (or costs) and the calculated CO_2 reductions. In the Annex we have illustrated the shadow price calculations for three different policy initiatives. The assumed prices on charging infrastructure have, however, been assumed at rather low prices in these calculations (a charging pole is set at a price close to 1500 Euro and a fast charging station at 75,000 Euro[4]). For further details about these calculations we refer to Kveiborg et al. (2009).

DISCUSSION

The investment in recharging infrastructure influences demand, but it also influences the welfare economic impacts, which is a decision criterion in many transport policy designs. We combine our findings from the estimated model and the analysis of recharging necessity with the actual costs of supplying the necessary infrastructure.

Policies that influence car buyers' willingness to buy an electric vehicle are estimated in the described demand model. Decision makers have only very few available instruments to use in this support. One instrument is the price (taxes and subsidies) another is the investment in the infrastructure. It is not obvious which of these alternatives may prove to be the most efficient seen from a socioeconomic point of view. Our analysis clearly showed that the price instrument is limited in its capability whereas e.g. investments in charging infrastructure can make a big difference. This is mainly due to the larger scope for making changes (from the present very low accessibility to recharging to a level that can meet all users' demand). The calculation of the shadow prices is n analytical method that can help decision makers in choosing between available instruments. Our investigations indicate that the costs per electric vehicle (her measured as reduced CO_2) are very similar across different measures. The indicated shadow prices are all rather high (from 866 DKK and up) compared to alternative initiatives to reduce CO_2. The price we can use for comparison is the CO_2 price on the European Trading Scheme market. This price is close to 150 DKK and thus much lower than the shadow prices reported here. Moreover, some studies (e.g. Jochen et al., 2008) have indicated that there are several initiatives with relatively low (and some even negative) shadow prices.

The main problem remains to be the price of the vehicle and the battery. In Denmark a main part of this is due to the high car purchase tax, which means that every time a conventional car is shifted to an electric car, the government will loose a large revenue. At current prices of electric vehicles this is not balanced out by an increased benefit for the users.

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[4] We do not have a precise estimate of the prices of these charging facilities and have thus assumed conservative and low values.

It can be discussed whether our approach to calculate the shadow price reveals the true shadow price. If the initiatives to invest in charging infrastructure and facilities are made independently by a private entrepreneur, who envisions the investment as a market potential, an amount of electric vehicles will come irrespective of government initiatives. This obviously reduces both costs and benefits of the electric cars that follow this private initiative. Moreover, the extent to which the costs of installing large parts of the infrastructure should be allocated to the introduction of electric vehicles can also be debated. It may be that these costs are rather part of the power industry's investments in green power supply.

We have not investigated how such alternative interpretations will affect the shadow price. However, since the major part of the costs and benefits are proportional to the number of electric cars that will be bought as a consequence of a particular policy (e.g. the prolongation of the tax exemption), we will probably only discover minor changes in the shadow price.

Our analyses are rather simple in the setup and there are naturally a number of limitations in the investigations, which to a large extent is due to lack of information about user behaviour in relation to electric vehicles. Here we will highlight some of the main limitations.

Limitations in the demand model

Since the focus of this paper is the interactions among several modelling approaches, a simple demand model was chosen. The demand model is estimated as an MNL model). This does not take the repeated nature of the panel data into account. Secondly we add a fuel availability parameter from another study. To do so we assume that fuel availability, which is an infrastructure attribute, is uncorrelated with the other attributes, which are technology attributes. Given the different nature of these attributes, this approach seems reasonable. Finally we maintain the scale set by SP estimation. Even though this has no effect on the WTP measures it could affect elasticities. Here we rely on Mabit (2009) who establish that the SP study gives elasticities that resembles revealed preference elasticities for the Danish market.

Limitations in the analysis of recharging

The problem of using data for conventional cars for the analyses is that people may very well change their transportation pattern when they get used to an electric vehicle. And more important, it will not be a random selection of the population that will buy an electric car, but rather people who have a transport behaviour that is suitable for using electric vehicles. This means that the analyses presented in this paper will not be representative for how electric vehicles in the car fleet will charge.

The available travel data can be used for analysing travel behaviour for two kinds of purposes. The first purpose is to elucidate how suitable electric vehicles will be for fulfilling the need for travel behaviour, and the other is how the electric vehicles will interact with the electric grid. However, the answer to the last question is dependent on the future electric

vehicle car stock and the behaviour of the electric vehicle car owners. And this depends on how inclined different groups are to buy an electric vehicle as the only or as the second car and how much they will drive. So the two questions are closely related.

Therefore more effort has to be done both on developing a car driving model which can explain how the car driving pattern is and on a demand model for electric vehicles. The actual paper is only an introduction to the relevant analyses.

Market penetration of electric vehicles, what are the barriers

Our analysis shows that accessibility to recharging is a central factor in car users' demand for electric vehicles based on the responses given in the SP data and the estimated model. However, this only relates to the statements and not necessarily to the actual driving behaviour of car users.

The analyses show that only very few one car owners can do without the possibility to charge outside home. Therefore development of a charging pole infrastructure will be an absolute prerequisite for getting the electric vehicles spread in a mass consumption market. Until this will be the case it cannot be expected that even electric vehicles with a large travel range of e.g. 160 km will be common.

More car owners can do without fast charging facilities at least for a period of a week to a month. So the existents of only an extensive network of fast charging facilities will be enough for the first years. But of course this will result in much higher share of electric vehicles as car number two than as the only car of the family.

Table 8 Charged travel range dependent on the parking time

Charging time:	10 min	30 min	1 hour	2 hours	3 hours
10 Amp:	4 km	12 km	24 km	48 km	72 km
16 Amp:	6 km	19 km	38 km	77 km	115 km

It is also worse to be aware that 400 Volt powered charging poles with 16 ampere current will suit many purposes so that fast charging is only needed for long distance travels. According to Table 8 in 3 hours which is much less than a normal working day, extra 115 km can be added to the travel distance. This means that everybody will be able to get home again after a working day independent of how discharged the car is when they arrive. And even half an hour makes it possible to get home from a shopping trip for most people, if the battery was almost discharged when the car was parked.

The difficulty in our analysis of the market for electric vehicles is that the exact relationship between installation of charging infrastructure and the perception of accessibility of recharging is not directly established from the analysis of the need for recharging. Our investigations was thus based on the relation between number of parking slots and fuel stations on one hand and the potential market size on the other. This is naturally a rather subjective assessment. We have therefore looked at the impact that accessibility has on

market demand independent from the investments in charging infrastructures by altering the level of accessibility in the forecasts. Moreover we have also indicated how delayed investments in infrastructure influence the market penetration. The delay not only influence the share of electric vehicles in new sales in the years where accessibility is reduced, but through this also the accumulated number of electric vehicles.

The question we have not been able to answer through our investigations is whether accessibility in reality plays a central role. We have not established the exact relationship between the available infrastructure and the perception of accessibility. It may thus happen that the accessibility level is relatively high even with a low level of available infrastructure. The analyses of demand for recharging and fast charging give some support for this hypothesis since the need is limited.

However, if electric vehicles are expected to be a substitute for a conventional car, there is an obvious need for recharging facilities spread out geographically. Driving patterns over longer periods of time will eventually lead to demand for recharging in different locations and in order to meet this need facilities must be installed in all locations. Hence, accessibility may be considered relatively low, if investments are kept at a low level.

CONCLUSION

Electric vehicles are seen as one of the main private transport means of the future. Many stakeholders are interested in an increased market penetration from a business point of view, from a fuel supply point of view and from an environmental and climate point of view. Different initiatives aimed at supporting the mass introduction are proposed by governments and the EU (e.g. through the Green Car Initiative). So far little has been known about the relation between these initiatives and how they may generate additional demand for electric vehicles. The investigations that are brought forward by researchers and policy makers are addressing issues that are believed to have an impact, but often these impacts are not quantified and it is therefore difficult to assess whether they are in fact good ideas.

Our analyses address these issues. The problem of operation range is often claimed to be the most important barrier against a mass introduction of electric vehicles and many policies are aimed at compensating for that. We have investigated to what extent this may be a real problem in actual driving patterns using conventional vehicles and we have included this into a discrete choice model for purchase of electric vehicles. The estimated model confirms that the accessibility to recharging is an important issue that must be dealt with. However, we also have shown that it is only in limited situations recharging and fast charging is actually necessary during the day.

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ANNEX

Assumptions concerning variables in the model

	Unit	Source	2010	2020
Conventional car				
Price excl. Tax	1000 2008-DKK	Danish Unit costs	81	81
VAT (25%)	1000 2008-DKK		20	20
Purchase tax	1000 2008-DKK	2009 values	109	109
Registration fee	1000 2008-DKK	Skat.dk	2	2
Total price	*1000 2008-DKK*		*213*	*213*
Fuel price	2008-DKK/liter	Danish Unit costs	12,2	12,2
Fuel efficiency	km/liter	Danish Unit costs	12,9	16,0
Fuel costs	2008-DKK/km		95	77
Motor oil	2008-DKK/km	Danish Unit costs	3	3
Other variable operation costs	2008-DKK/km	Danish Unit costs	48	48
Annual user tax	2008-DKK/km	Danish Unit costs	21	21
Total operation costs	*2008-DKK/km*		*166*	*148*
Acceleration	Sek. 0-100 Km/h	Average from car sales database	12	12
Operation range	Km	Average from car sales database	700	700
Electric car				
Price excl. Tax and battery	1000 2008-DKK	DONG Energy	96	96
VAT (25%)	1000 2008-DKK		24	24
Purchase tax	1000 2008-DKK	2009 values	0	20
Battery price	1000 2008-DKK	Cowi (2009)	50	30
VAT (25%)	1000 2008-DKK		13	7
Purchase tax	1000 2008-DKK	2009 values	0	0
Registration fee	1000 2008-DKK	Skat.dk	2	2
Total EV price	*1000 2008-DKK*		*185*	*180*
Price electricity	2008-DKK/kWh	Danish Unit costs	1.88	1.88
Taxes on electricity	2008-DKK/kWh	Danish Unit costs	1.06	1.06
Price reduction, night charging	2008-DKK/kWh	Copenhagen Economics (2008)	-0.08	-0.12
Share night charging		Assumption	75%	75%
Effective electricity price	2008-DKK/kWh	Danish Unit costs	182	1.79
Energy efficiency	km/kWh	Danish Unit costs	0.073	0.08
Electricity total	*2008-DKK/km*		*0.25*	*0.22*
Other operating costs	2008-DKK/km	Danish Unit costs	0.48	0.48
Annual user tax	2008-DKK/km	Energy agreement 21/2 2008[1]	0	0
Total operation costs	*2008-DKK/km*		*0.72*	*0.70*

	Unit	Source	2010	2020
Conventional car				
Acceleration	Sek. 0-100 Km/h	Ingeniøren/assumption	14	14
Operating range	km	i-Miev / Ingeniøren	160	215
		Annual growth 3 %		

[1] Electric vehicles are exempted from purchase tax until 2012, but current tax levels render the tax close to zero also after 2012.

Other assumptions

	Unit	Source	2010	2020
Annual km	Km	Cowi (2009)	18.000	18.000
		Infrastructure		
Car stock	1000.	Commission (2008)	2.264	2.500
New sales as share of car stock		Historical average	7%	7%
Fuel tax	2008-DKK/km	Danish unit costs	0.23	0.23
Electricity tax	2008-DKK/km	Danish unit costs	0.09	0.08

Shadow prices on CO_2 reductions following a welfare economic calculation

	Basis and tax exemption	Tax exempt. And no tax on electricity	Head start in infrastructure
Total CO_2 reduction (Ton)	1,312,000	1,515,000	2,091,000
Net present value (million DKK)	-1,399	-1,532	-1,849
Of which			
User benefits	*4,618*	*6,042*	*7,441*
Investments (Private only)	*-1,859*	*-1.895*	*2.193*
Externalities (noise, emissions)	*1,361*	*1,556*	*1,882*
Tax revenue effects	*-4,694*	*-6,140*	*7,703*
MCPF	*-939*	*-1,228*	*-1,541*
Shadow price. (DKK/TON) All infrastructure is privately financed	1,066	1,011	884