

Optimal regulatory policies for charging of electric vehicles

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Abstract

Electric vehicles (EVs) and their associated charging stations are characterized by indirect network effects. Indirect network effects may imply too slow adoption of a new good that improves welfare. Today, there are at four standards for high-speed charging in Europe. We find that policies should seek to standardize high-speed charging systems as this will unambiguously mean faster phase-in of EVs and improve welfare. We also find that governments should subsidize both the charging at each station and the entry of charging stations. The subsidies should cover a share of the private variable charging cost and the private fixed entry cost. Furthermore, the formula for setting the shares of costs to be paid by the regulator turns out to be very simple; the regulator only has to observe the percentage markup on the charging price, and can calculate the optimal share directly from that.

Keywords: EV policy, indirect network effects, EV charging

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1 Introduction

In order for emissions from road transport to be consistent with IEA's 2 degree C target trajectory, the diffusion of electric vehicles (EVs) must speed up (IEA, 2017). Today, most governments in the EU provide subsidies to consumers that buy an EV (Bjerkan et al. 2016). The diffusion of EVs is, however, not only dependent on policies directed at the EVs. According to an increasing body of literature, the extent and quality of the charging network is also a major factor (Jensen et al. 2013; Zhang et al. 2016; Zarazua de Rubens et al. 2020).

Today, there are four standards for charging in Europe. The two most widespread are Combo and Chademo; the former applying to most European made cars, while the latter applying to mostly Asian cars (Kanger et al. 2019). Then there is a standard based on AC current, and finally, a fourth standard owned by Tesla Motors. According to press statements, also some German car manufacturers plan to build their own charging network. In 2014 the EU adopted a directive *on the deployment of alternative fuels infrastructure*, however, according to Transport and the Environment (2020) the directive already needs to be significantly updated.

In this paper we apply a theoretical economic model to investigate optimal regulatory policies for charging of EVs. First, we find that policies should seek to standardize high-speed charging systems as this will unambiguously mean faster phase-in of electric vehicles. In order to illustrate this effect, we calibrate our model to Norwegian data, and find that market shares could have been increased with several percentage points if charging systems had been compatible.

Second, we also find that governments should subsidize both the charging at each station and the entry of charging stations. Due to spatial differentiation, charging prices include a high mark-up, and the charging subsidy

ensures marginal cost pricing. Still, without an entry subsidy, the network will be insufficient since electric vehicle owners do not internalize the positive effect their charging have on the network and thereby on other EV owners.

Third, we look at public subsidies that covers a given share of the private variable charging cost and the private fixed entry cost. Interestingly, we find that the formula for setting the share of costs to be paid by the regulator is very simple; the regulator only has to observe the percentage markup on the charging price, and can calculate the optimal share directly from that.

Other papers have also looked at optimal regulatory policies for charging of EVs in theoretical models (Zhou and Li 2018; Meunier and Ponsard 2020). On the other hand, the existing literature does not to capture two central features of the market for EV charging; all fast charging stations include a large mark-up on their charging price, and there currently exist several different charging standards. Thus, this paper contributes to the literature by introducing different charging standards and monopolistic competition between charging stations.

Finally, we question whether an optimal policy for charging of EVs makes other EV deployment policies redundant. We find that subsidies to EVs are superfluous if both charging of EVs and entry of charging stations are subsidized, moreover competition between EV suppliers is perfect, and lastly, the environmental externality of internal combustion cars is internalized. Clearly, all these conditions are rarely satisfied in real markets.

The rest of the paper is laid out as follows: In the next section we discuss the relevant literature. The model is presented in Section 3, and in Section 4 we look at the market equilibrium. Section 5 covers optimal policies, while Section 6 includes the numerical example from Norway. In Section 7 we discuss the standardization issue, and in Section 8 we discuss our results in general. In Section 9 we conclude.

2 Literature

According to Farrell and Klemperer (2007), the consumption of a good has positive network effects if one agent's purchase of the good i) increases the utility to all others who possess the good and ii) increases the incentive of other agents to purchase the good. Recent research suggests that the diffusion of EVs is affected by indirect network effects since the consumers' willingness to pay for EVs depends on the extension of the charging network which again depends on the number of EVs in the car fleet. Li et al (2017) use data from the US and estimate a model which combines EV sales with charging station stocks. They find that a 10% increase in the stock of charging stations will increase EV demand by 8%. Network effects in private transportation is also found for other types of fuel see e.g. Corts (2010) for a study of the role out of ethanol (E85) fueling stations. Finally, the interrelationship between charging stations and EVs is confirmed in Sierzchula et al. (2014), which find looking at a panel of 30 countries, that the size of the charging network correlates strongly with the market share of EVs.

There is much to indicate that in particular the availability of high-speed charging will be important for the future sales of EVs. Illmann and Kluge (2020) emphasize charging speed as essential for EV uptake. Figenbaum and Kolbenstvedt (2016) report from a survey in which availability of high speed charging stand out as one of the major factors affecting the utility of an EV. High-speed charging makes long distance driving possible with EVs. Research shows that for a majority of potential EV owners it is important to be able to drive long distances; for instance, Daziano (2013) and Hidrue et al. (2011) find, using different methods, that willingness to pay for 10 km extra driving distance is between € 130 and € 390.

There are also several theoretical contributions looking at network effects in the car market. Sartzetakis and Tsigaris (2005) consider a model with

infinitely-lived cars. They assume that a shift to clean cars is socially desirable, and find that the tax on dirty cars may exceed marginal environmental damage in order to accomplish the shift. Greaker and Midttømme (2016) extends the analysis of Sartzetakis and Tsigaris (2005). They consider the Markov perfect equilibrium in an infinite game between a government, car producers and car consumers. If the old network good entails environmental externalities, and the new network does not, Greaker and Midttømme (2016) find that taxing the dirty network far above the Pigouvian rate may be desirable in order to facilitate a rapid transition to the clean network good.

On the other hand, these two contributions do not model the indirect network effect explicitly. Greaker and Heggedahl (2010) include both the market for cars and the market for alternative refueling technologies. They are then able to discuss the different factors leading to a lock-in in the old fuel technology. However, Greaker and Heggedahl (2010) do not consider different standards for the new fuel, a factor that further complicates the picture. They also do not look at the optimal use of policy instruments aimed at increasing the supply of the new fuel.

Meunier and Ponsard (2020) extend the analysis of Greaker and Heggedahl (2010) in several directions, and in particular, they analyze the optimal use of policy instruments. They find that the optimal EV policy includes both subsidies to the charging network and the EVs, however, they include more market failures than the network externality e.g. increasing returns to scale in production of EVs.

The significance of charging compatibility for EVs is a new research topic. We are only aware of one empirical study from the US, where there are also several charging standards. In this study, Li (2016) finds that compatibility results in more EVs, but fewer charging stations overall. Welfare also increases substantially with full compatibility. This is consistent with the predictions

emerging from our theoretical model.

Our model builds on Katz and Shapiro's (1985) model of network competition. In this seminal paper Katz and Shapiro study private firms' incentives to offer compatible network goods without being explicit on the nature of the network externality. Thus, we combine Katz and Shapiro's (1985) model of network competition with Oz and Shy's (1990) model of indirect network effects. The result is a model in which EVs compete with petrol cars, and the entry of charging stations of different types happens endogenously as a response to EV sales of the different types.

3 The model

3.1 Preliminaries

Chargers with an effect of 40 kilo watts (kW) or more are coined high-speed chargers. The economy of high-speed charging is characterized by large fixed costs for the station itself, the necessary land and grid connection, but low marginal production costs in the form of power.¹

In our model, we have three types of economic agents; consumers, high speed charging station owners and EV manufacturers. Consumers choose an EV or a internal combustion engine car (ICE), and if they choose an EV, they decide how much to use high speed charging. Charging station owners decide whether to enter the market, and EV manufacturers must resolve how many EVs of their type they should offer to the market. The decisions of the three kinds of agents are interlinked through the indirect network effect e.g. the demand for an EV type depends on the number of charging stations being compatible with the EV type and *vice versa*.

As mentioned, there are four standards for high-speed charging in Europe. Outlets seem to be primarily owned by various power companies such as

¹See for instance Shroeder and Traber (2011).

Fortum and Statkraft, but other actors are also involved such as the gasoline station chain Circle K. Many, but not all outlets, have received investment subsidies from various governments in the EU. As far as we know, Tesla is currently the only car company that also provides charging. As the other stations, they demand payment for charging.

As a simplification, we assume that the usage of private cars is given, and that all consumers have either an ICE or an EV. Since both the usage of a car and total car demand is given, it does not matter in the model whether the government chooses an environmental tax on ICEs or an environmental subsidy to EVs. Furthermore, we normalize both the willingness to pay for a petrol car and the price of a petrol car to zero. These assumptions does not affect the main results of the analysis.

Finally, we do not model the network of gasoline/diesel filling stations. This network is already established, and we assume that it will be around in the intermediate term independent of the sales of ICE cars.

3.2 Consumers' utility of EVs

Consumers are heterogenous with respect to how much they are willing to pay for an EV. On the other hand, like in Katz and Shapiro (1985), we assume that the n EV car types only differ by their charging network. In order to model the charging network, we use the monopolistic competition model. The underlying assumption is that each charging station j providing a certain charging standard i is spatially differentiated to the other charging stations $-j$ with the same standard i .

Denote by M_i the number of charging stations of type i entering the market. Moreover, assume a representative EV owner with a given income I . The indirect utility consumers' gain from an EV can then be expressed as (with charging system i):

$$u_i = (I - p_i - E) + r + \kappa \left(\left(\sum_{j=1}^{M_i} (q_j)^\rho \right)^{\frac{1}{\rho}} \right)^\beta \quad (1)$$

where p_i is the price of an EV, E is total spending on charging, r is the utility from the car itself, and the last term in (1) is the utility from the charging network. We assume that r is uniformly distributed on $\langle -\infty, A \rangle$, where A is the maximum a consumer is willing to pay for an EV (not taking into account the charging network).

For the utility of the charging network, κ is a scaling parameter and q_j is the number of charges from station j (we suppress the notation i here). The parameter $\rho < 1$, indicates to what degree the different stations within a network can substitute each other. Moreover, we impose $\beta < \rho$ to ensure that the marginal benefit of an extra charging station is declining. In order to simplify the derivation of the reduced form expressions, we fix β such that $\beta = \rho/(2 - \rho)$ e.g. $\rho = 1/2$ yields $\beta = 1/3$ etc.

Let the price of a standard charge be denoted ω_j . For E , the total spending on charging, we then have $E = \sum_{j=1}^{M_i} \omega_j q_j$. By maximizing (1) with respect to q_j , we find each EV owner's demand for charging. Each charging station owner then maximizes profit with respect to the charging price in line with the monopolistic competition model. We then obtain the equilibrium demand for charging q^* and the equilibrium price of charging $\omega^* = \psi(1 - \xi)/\rho$.²

3.3 Equilibrium in the charging market

Denote by y_i^e the number of consumers that is expected to have an EV of type i which can use the charging network i . Total demand for charging at a station is then given by $y_i^e q^*$. We set the private marginal cost of charging to

²Since the monopolistic competition model is well known, the full derivation of the equilibrium in the charging market is in the Appendix. Furthermore, we can drop the subscript j , because in equilibrium all stations within a network will have identical demand.

$\psi(1 - \xi)$ for all stations where ξ is a subsidy to charging. Furthermore, there is a fixed cost $f(1 - \sigma)$ of setting up a charging station, where σ is a subsidy to charging station investments. Equilibrium in the market for charging then requires $(\omega^* - \psi(1 - \xi))y_i^e q^* - f(1 - \sigma) = 0$ e.g. profit on charging should be equal to fixed cost.

In the Appendix we solve the model for the market equilibrium levels of q , M_i and E . The reduced form expressions for q , M_i and E can then be fed back into (1), to yield the following reduced form expression for indirect utility:

$$u_i = I - p_i + r + \theta y_i^e \quad (2)$$

where

$$\theta = \left(\frac{\rho \kappa}{2 - \rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1 - \xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1 - \rho)^2}{f(1 - \sigma)\rho}$$

Thus, the individual utility of owning an EV of type i is dependent on the number of other owners of an EV with the same charging system i .³ Note that on the reduced form in (2), our model looks exactly like a direct network externality model like for instance the one in Greaker and Midttømme (2016). The size of the parameter θ determines the strength of the network effect. It increases in κ and the two network subsidies σ and ξ , and decreases in the fixed and variable costs of charging f and ψ .

To understand the mechanism behind the network effects, we need to look at the equilibrium number of charging stations in each network i :

$$M_i^* = \theta \frac{\rho(y_i^e)^2}{2f(1 - \sigma)} \quad (3)$$

Note that the number of charging stations in a network M_i is convex and

³Fixing β to $\rho/(2 - \rho)$ implies that utility is linear in the network benefit. This is a standard assumption in the literature on network effects.

increasing in y_i^e e.g. the number of consumers that is expected to have an EV of type i . Thus, splitting demand for EVs into more than one network inevitably leads to fewer stations in each network.

3.4 Demand and supply of EVs

As already stated p_i denotes the price of an EV of type i . We let s be an environmental subsidy for buying an EV. Since the willingness to pay for a petrol car and the price of a petrol car is normalized to zero, all consumers with net utility from an EV: $r + \theta y_i^e + s - p_i \geq 0$ will buy an EV. Because $r \sim [-\infty, A]$, we have that $A - (p_i - \theta y_i^e - s)$ consumers will buy an EV. Hence, for given network size expectations, each EV manufacturer will face an ordinary linear demand curve that can be expressed as follows:

$$p_i = A + \theta y_i^e + s - \sum_i x_i \quad (4)$$

where the last term is total sales of EVs. We assume $\theta < 1$ in order to ensure a downward sloping demand curve when $y_i^e = \sum_i x_i$ e.g. in a fulfilled expectations equilibrium with one standardized network.

There are n EV producers, each indexed by i , which supplies x_i EVs of type i to the market. We set the extra costs of manufacturing an EV compared to a gasoline car equal to c for all n types of EVs. We assume Cournot competition between the n EV manufacturers. The n EV manufacturers then solve the following maximization problem:

$$\max_{x_i} \left\{ \left(A + s + \theta y_i^e - \sum_i x_i - c \right) x_i \right\} \quad (5)$$

Following Katz and Shapiro (1986), we assume that firms take consumer expectations as given when they fix quantity (and hence the charging network). Furthermore, as in general for Cournot competition, each EV firm

takes the production quantity of the other manufacturers as a given. The first-order condition for firm i is given by:

$$A + s + \theta y_i^e - \sum_i x_i - c - x_i = 0 \quad (6)$$

where $d(\theta y_i^e)/dx_i = 0$ by assumption.

Note that since we by (6) have $x_i = p_i - c$, the profit of the EV firm π_i is equal to $(x_i)^2$.

4 The fulfilled expectations equilibrium

The equilibrium concept we use is more extensive than a traditional Nash equilibrium, and is described by Katz and Shapiro (1986) as a “fulfilled expectations equilibrium”. In other words, both the consumers’ and the charging station owners’ expectations about the networks for the various car types are correct in equilibrium, and in addition the manufacturers have made their best choice given the other manufacturers’ choices, as in a Nash equilibrium. The set of equations are then relatively easy to solve as long as we assume symmetrical companies and symmetrical networks.

Let $\mu \leq n$ denote the number of networks, and x^* the equilibrium output of the n EV manufactures. We then have $y_i^e = nx^*/\mu$. By solving for x^* in (6) we get:

$$x^* = \frac{A + s - c}{n + 1 - \frac{\theta}{\mu}n} \quad (7)$$

By inspection of (6), and remembering that $\partial\theta/\partial\sigma, \partial\theta/\partial\xi > 0$, we have:

Proposition 1 *A higher degree of compatibility, e.g. fewer charging networks, will result in more EVs sold in equilibrium. Introducing a subsidy to charging stations σ and/or a charging subsidy ξ and/or a subsidy to EVs s will also result in more EVs sold in equilibrium.*

Since $\pi^* = (x^*)^2$, it directly follows that in the symmetric equilibrium, compatibility leads to higher producer surplus. Thus, given that the EV manufactures could achieve compatibility without incurring costs, they would agree to do so. On the other hand, we should not expect that changing charging standard is free for the EV firms as they historically have invested in a certain system.

5 Optimal combination of policies

5.1 First best

In the following we derive an expression for welfare. Due to our normalization the individual consumer surplus from a petrol car is zero, while the individual consumer surplus from an EV is equal to $r + \theta (nx^*/\mu) + s - p^*$. Inserting for p^* from the demand function (4), individual consumer surplus can alternatively be written as $r + nx^* - A$. Only those consumers with a non-negative surplus will buy an EV e.g. $r \geq A - nx^*$, and hence for the overall consumer surplus we have:

$$CS = \int_{A-nx^*}^A (S + nx^* - A) dS = \frac{(nx^*)^2}{2}$$

Thus, as for producer surplus, it directly follows that in the symmetric equilibrium, compatibility leads to higher consumer surplus.

Finally, let the cost of emissions per petrol car be given by δ . Welfare W is then given by the following expression:

$$W = \frac{(nx^*)^2}{2} + n(x^*)^2 + \delta nx^* - snx^* - \psi \xi q^* nx^* \mu M^* - \sigma \mu f M^* \quad (8)$$

where the terms in (8) are from left to right; consumer surplus, producer sur-

plus, the reduction in environmental damage from EV sales⁴, the EV subsidy cost, the charging subsidy cost and the charging station subsidy cost. Note that the producer surplus from the charging network is not included in the welfare expression since the charging station owners per assumption earn zero profit.

The price of charging is $\psi(1 - \xi)/\rho$. Hence, in order to set the charging price equal to marginal cost, the government must set $\xi^* = 1 - \rho$. Inserting for ξ^* into the welfare expression (8), and taking the derivatives of welfare with respect to the number of networks and the two remaining policy instruments we obtain:⁵

$$\begin{aligned}\frac{\partial W}{\partial \mu} &= \left[nx^* + 2x^* + \delta - s - \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{d\mu} - fM^* \\ \frac{\partial W}{\partial s} &= \left[nx^* + 2x^* + \delta - s - \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{ds} - nx^* \\ \frac{\partial W}{\partial \sigma} &= \left[nx^* + 2x^* + \delta - s - \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{d\sigma} - \mu f \frac{\partial M^*}{\partial \sigma}\end{aligned}\quad (9)$$

We have the following proposition:

Proposition 2 *With the three subsidies ξ , σ and s set optimally e.g. $\partial W/\partial s = \partial W/\partial \sigma = 0$, a higher degree of compatibility always increases welfare in the long run equilibrium.*

Proof. From the expressions for $\partial W/\partial s$ and $\partial W/\partial \sigma$ we see that the terms in brackets has to be *positive* in order for $\partial W/\partial s = \partial W/\partial \sigma = 0$. Since $dx^*/d\mu < 0$, we must have $\partial W/\partial \mu < 0$. The proposition then follows. ■

Solving the two equations $\partial W/\partial s = \partial W/\partial \sigma = 0$, will yield the optimal set of subsidies. For the optimal charging station entry subsidy we have:

⁴Remember the assumption that total demand for cars is constant in the long run equilibrium. The sale of EVs thus reduced one for one the sale of petrol cars.

⁵See the Appendix for the full derivation.

$$\xi^* = \sigma^* = 1 - \rho \quad (10)$$

Note that the rate by which the government should subsidize EV charging is exactly equal to the rate that it should subsidize the entry costs of charging stations. The rate does not depend on any other parameter. Hence, the government can simply observe the mark-up on the charging price, and then calculate the optimal charging station entry subsidy.

Proposition 3 *The optimal combination of the charging subsidy and the charging station entry subsidy is to set both rates equal to $1 - \rho$, which is directly proportional to the mark-up on the charging price.*

E.g. if the price of charging is four times the cost, we have $(1 - \rho)/\rho = 4$ implying that $\rho = 0.2$ and that the subsidy rate should be 80 percent.

Unfortunately, the reduced form expressions for the optimal EV subsidy becomes very messy. For the sake of exposition, we have therefore solved for $\partial W/\partial s = 0$ with $\rho = 0.5$. It is then fairly straight forward to show that:

$$s^* = \delta + \frac{A + \delta - c}{n \left(1 - \frac{2\kappa^3}{27\psi\mu f}\right)} \quad (11)$$

By assumption the denominator in (11) is positive.⁶ First, note that the EV subsidy goes towards δ when the number of EV suppliers goes towards infinity e.g. the perfect competition solution. Hence, perfect competition between EV suppliers and optimal subsidies to the charging network, make a subsidy in excess of the environmental benefits of EVs superfluous.

Second, note that as long as n is small, the EV subsidy is declining in the number of networks and the costs of charging (both ψ and f). On the other

⁶We assume $\theta < 1$. Since $\theta = 2\kappa^3/27\psi f$ when $\rho = 0.5$ and ξ and σ are set optimally and $\mu \geq 1$, $2\kappa^3/27\psi\mu f < 1$.

hand, it is increasing in the utility of the network κ and the maximum stand alone net utility of EVs ($A + \delta - c$) as compared to gasoline cars.

5.2 Second best

As far as we know from Norway and other European countries, EV owners pay the full price of charging, while both the entry costs of charging stations and the purchase of EVs may be subsidized.⁷

Below, we investigate the optimal combination of subsidies when $\xi = 0$. With $\xi = 0$, looking at (8), we see that welfare can be written: $W = (nx^*)^2/2 + n(x^*)^2 + \delta nx^* - snx^* - \sigma\mu fM^*$. By differentiating wrt. μ , s and σ , we obtain:

$$\begin{aligned}\frac{\partial W}{\partial \mu} &= \left[nx^* + 2x^* + \delta - s - \sigma\mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{d\mu} - \sigma f M^* \\ \frac{\partial W}{\partial s} &= \left[nx^* + 2x^* + \delta - s - \sigma\mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{ds} - nx^* \\ \frac{\partial W}{\partial \sigma} &= \left[nx^* + 2x^* + \delta - s - \sigma\mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{d\sigma} - \sigma\mu f \frac{\partial M^*}{\partial \sigma} - \mu f M^*\end{aligned}\tag{12}$$

By looking at the three derivatives of the welfare function, we note that we still have $\partial W/\partial \mu < 0$. Thus, Proposition 2 still holds; reducing the number of networks will increase welfare even if $\xi = 0$. Next, in the Appendix we solve for $\partial W/\partial \sigma = 0$, and show that the optimal subsidy to charging stations is given by:

$$\sigma^{**} = \frac{2 - \rho}{2 + \rho}$$

The charging station subsidy is decreasing in ρ . The intuition is that the larger the ρ , the less consumers value a large network e.g. a high M^* . Again, the optimal entry subsidy implies a simple rule for the government; it can

⁷See for instance Lorentzen et al (2017).

simply observe the mark-up on the charging price, and then calculate the optimal subsidy.

As above, we have solved for the optimal subsidy when $\rho = 0.5$ (see Appendix):

$$s^{**} = \delta + \frac{\frac{1}{n} + \frac{5}{432} \frac{\kappa^3}{\psi \mu f}}{1 - \frac{25}{432} \frac{\kappa^3}{\psi \mu f}} (A + \delta - c)$$

First, note that the EV subsidy no longer goes towards δ when the number of EV suppliers goes towards infinity e.g. the perfect competition solution. Hence, even with perfect competition between EV suppliers, the EV subsidy should exceed the environmental benefits of EVs when a charging subsidy is not available. As above, we also have that the EV subsidy is declining in the number of networks and the costs of charging (both ψ and f), while it is increasing in the utility of the network κ and the maximum stand alone net utility of EVs ($A + \delta - c$).

For the sake of completeness, we have also looked at the optimal EV subsidy when $\sigma = 0$ and $\xi = 1 - \rho$ e.g. there is no entry subsidy and the charging subsidy is set to ensure marginal cost pricing. In the Appendix we then show that the optimal EV subsidy when $\rho = 0.5$ is given by:

$$s^{***} = \delta + \frac{\frac{1}{n} + \frac{1}{54} \frac{\kappa^3}{\psi \mu f}}{1 - \frac{3}{54} \frac{\kappa^3}{\psi \mu f}} (A + \delta - c)$$

Again, we note that the EV subsidy no longer goes towards δ when the number of EV suppliers goes towards infinity e.g. the perfect competition solution.

Proposition 4 *If either $\xi = 0$ or $\sigma = 0$, there should be a subsidy to EVs in excess of the environmental benefits of EVs.*

5.3 EV sales target

In addition to deciding not to subsidize charging (e.g. $\xi = 0$), most EU governments have targets for the market share of EVs instead of allowing the EV sales to be endogenously determined by resolving for the optimal set of subsidies taking into account the size of δ . In our model a market share target for EVs can be expressed as a target for the number of EVs sold Ω . The welfare function can then be written: $\Omega^2/2 + \Omega^2/n - \Omega s - \sigma f \mu M^*$. Thus, in the case with a market share target, maximizing welfare is equivalent with minimizing the fiscal cost of the government: $s n x^* + \sigma f \mu M^*$ given $n x^* = \Omega$.

In the Appendix we show, assuming that the condition $n x^* = \Omega$ is binding, that the optimal charging station subsidy rate is given by:

$$\sigma^\Omega = \frac{2 - \rho}{2 + \rho}$$

Note that the optimal charging station subsidy should be set to a fixed value independent of the target e.g. 0.6 if $\rho = 0.5$. If $n x^* = \Omega$ is not binding when $\sigma = \sigma^\Omega$, the government may be tempted to set the subsidy rate lower. On the other hand, as shown above, $\sigma = \sigma^\Omega$ is optimal independent of δ such that a non-binding target just indicates that the target is too little ambitious.

Again, using $\rho = 0.5$, we have for the direct EV subsidy:

$$s^\Omega = \Omega \left(1 - \frac{5\kappa^3}{108\mu\psi f} + \frac{1}{n} \right) - A + c$$

The direct subsidy to EVs only comes into play if the target is not reached with $\sigma = \sigma^\Omega$. Since, as shown above, a positive subsidy anyhow is optimal (when $\xi = 0$), also $s^\Omega = 0$ indicates that the target is too little ambitious.

A higher fixed cost of charging stations f , a higher price on charging ψ , many networks μ or a higher market share target Ω , all makes the subsidy

larger.⁸ Decreasing cost of EVs, or increased expected utility from EVs (expressed by A), both make the subsidy smaller.

Proposition 5 *With a market share target for EVs, subsidizing the charging stations should only be pursued up to a maximum rate. Then, if the target is still not reached, EVs should be subsidized instead.*

6 Numerical illustration

In Norway subsidies to EV sales includes exception for the one-off registration tax, the value-added tax and fuel taxes including environmental taxes; see Bjerkan et al (2016). In 2019 EVs had a market share of 42% of new car sales, and EVs constituted nearly 10% of the car stock, and there is an ongoing discussion of scaling the down the subsidies.

There is also a subsidy program for charging stations with the goal to ensure that all major highways in Norway are covered with fast charging opportunities. In 2018 there were about 1500 separate fast charging points, that is, about 130 EVs per point. Charging for 100 km of driving costs less than 2 euro for electricity including grid rental. Nonetheless, the price of high-speed charging is currently between 5 and 10 euro.

Below we fit our model to a potential equilibrium in 2030 in which EVs have taken 40% of the car stock without the use of subsidies and with 4 different charging networks.⁹ Norwegian Environment Agency (2016) predicts that EVs and ICE cars will have similar production costs by 2030, and hence, we normalize the cost of an EV and an ICE both to zero. Moreover, we assume perfect competition and denote demand for EVs by z . We then have $z = (A + s)/(1 - \theta/\mu)$.

⁸By assumption, the expression in parentheses must be positive since $\theta = \frac{5\kappa^3}{108\psi f}$ when $\rho = 0.5$ and $\sigma = (2 - \rho)/(2 + \rho)$.

⁹According to Norwegian policy the target is to have about 40% EVs in the car stock by 2030, see Norwegian Public Roads Administration, 2016.

For some of the parameters we have reasonable estimates; the cost of electricity ψ , the mark-up on fast charging (determines ρ) and the environmental costs of ICE cars δ .¹⁰ However, for κ , A and f , we rely on a "calibration" procedure. The parameters κ and f jointly determines the number of charging locations and the elasticity of demand for EVs with respect the the number of locations, $El_{x,M}$. Hence, first we set κ and f specifying the number of EVs per charging outlet in a network, $z/\mu M_i$ and $El_{x,M}$, which Li et al. (2017) reports to be as high as 8%. Then, we set A e.g. the maximum willingness to pay for an EV relative to an ICE, such that a market share of 40% is reached.

Having "calibrated" the model to a hypothetical 2030-equilibrium, we simulate the model to look at the effect of standardization of charging. Below we report two simulations. In all simulations the charging station entry subsidy is optimally set, but there is no charging subsidy e.g. $\sigma = 0.6$ and $\xi = 0$. One finding is that the model is very sensitive to $El_{x,M}$, and for numbers above 2% the effect of standardization seems unlikely large.

Figure 1 "The market effects of compatibility"

Figure 1 to be placed here

First, note that for both $El_{x,M} = 0.02$ and for $El_{x,M} = 0.01$, introducing $\sigma = 0.6$ has a moderate effect on the market share of EVs; the market share increases from 40 to 42,7% and from 40 to 41,3% respectively. Second, for both $El_{x,M} = 0.02$ and for $El_{x,M} = 0.01$, there is a strong effect of full standardization: With $El_{x,M} = 2\%$ EVs reach 64% market share as compared to 42,7% with 4 networks, while with $El_{x,M} = 1\%$ EVs reach 49% market share as compared to 41,3% with 4 networks.

¹⁰See the Appendix for the chosen numbers.

Next, we use $El_{x,M} = 0.01$ and look at the optimal combination of the subsidies s and σ with more ambitious targets than 40% of the car stock. With 4 networks both kinds of subsidies must be used to increase the market share of EVs above 41,3%. For instance, we see that a target of 50%, requires EV subsidies in the range of €200.000! However, with full standardization, you nearly reach 50% with only charging station entry subsidies.

Figure 2 "EV subsidies with market share target"

Figure 2 to be placed here

Note that is optimal from a welfare point of view to use EV subsidies in addition to the charging station entry subsidy. In the case with 4 networks, the optimal EV subsidy is €31019, which is double the environmental costs of the ICE car the EV replaces¹¹. In the case with full standardization the optimal EV subsidy is € 89778, which is even higher than the current Norwegian EV subsidies. The optimal EV market share in the case of 4 or 1 network is 42,4% and 53,1%, respectively. Although these simulations should only be regarded as illustrations of the effects of standardization, we are tempted to conclude that standardization might be the most important part of future EV policies.

7 Private incentives to promote compatibility

We find that policies should seek to standardize high-speed charging systems as this will unambiguously mean faster phase-in of electric vehicles and increased welfare. If it is easy to make the charging technologies compatible, the overall profit of the EV industry also increases in our model. One could therefore expect them to coordinate amongst themselves, and promote a common

¹¹Based on current CO_2 taxes in Norway, the average lifetime environmental cost of an ICE car is € 16330.

charging standard. However, that is not always what we observe in markets with network externalities (Farrell and Simcoe, 2012).

It is possible that there are substantial costs entailed in developing a common high-speed charging technology that is suitable for the various EVs. As we understand it, the Opel Ampera, for example, which has a real range of 300 km, would not manage 120 kW charging like a Tesla. The costs may be both technological and organizational, in terms of the time and effort involved in negotiating for a common standard. It may therefore be unprofitable for companies to invest in compatibility, even if it is profitable from a socioeconomic point of view.

Nor is it certain that all manufacturers would benefit from a common standard, even though introducing a common standard is in principle free of charge. In a separate note we examine this in more detail by looking at two asymmetric firms; one of them having a better charging technology than the other. Our main finding is that even when discounting the costs of creating a common standard, the manufacturer with the superior charging system prefers incompatibility.¹² Thus, it is not a given that the market itself will arrive at a common standard, even if there are no technological obstacles in the way.

Farrell and Simcoe (2011) discuss three other ways to a common standard: i) through a standards organization, ii) through compulsion from authorities or big customers and iii) through broad distribution of adapters. Adapters between Chademo and Combo chargers are already in use, but technical differences among cars may make this more difficult in the future. In all cases adapters come at a price and occupy space in the car, which still makes compatibility desirable.

Standard-setting organizations are usually based on consensual decisions,

¹²The author is happy to share the note upon request.

which may be difficult to achieve when one of the participants has gained a head start. In the current phase, it looks as though EV suppliers may be choosing a strategy that involves developing separate solutions. For instance, prominent carmakers such as BMW, Ford, VW and Mercedes have launched plans for a new, faster charging network.

We are then left with what Farrell and Simcoe (2011) call the “dictator” solution, where the authorities set the standard. In view of EU politicians’ ambitious climate goals, it seems like a good policy to get high-speed charging standardized. On the other hand, there are large multinational companies behind the various makers of EVs, and these companies may of course object, and argue that this imposes extra costs. On the other hand, car companies are used to tailor-made cars for specific markets e.g. left- and right-hand steering. Patents can also prevent the “dictator” solution e.g. European car makers can deny "foreign" car makers to use their standard. Patent buy out is then an option which should be considered.

According to Farrell and Saloner (1986) and Farrell and Simcoe (2011), mandatory standardization could also inhibit technological development and lead to lock-in to an inferior standard. Society may be benefiting more at present from the fact that the different car manufacturers are trying to produce better and faster chargers, than they would from full standardization of charging today. Katz and Shapiro (1986) find that manufacturers may prefer standards as a means of reducing competition. In other words, by choosing compatible technologies, companies avoid a phase of intense competition, with each manufacturer using low prices to build up his own network and get ahead of his rivals. On the other hand, if this competition leads to technological development it may be beneficial from a socioeconomic point of view. A social planner with a long time perspective may therefore find the optimal solution to be to encourage competition in an early phase of rapid

technological development, and then introduce a standard later on.

8 Discussion

The general literature on network economies has discussed to what extent indirect network effects constitute a market failure. Liebowitz and Margolis (1994) argue that history has shown that markets handle indirect network effects well without governments having intervened. On the other hand, several papers e.g. Meunier and Ponsard (2020) and this paper, now provides theoretical arguments for government intervention also in the case of indirect network effects. Hence, a carefully crafted policy for the diffusion of EVs may be essential for reaching the already agreed EU emission reduction targets.

In the real world matters are more complicated than in our stylized model. First, in our model all charging stations have the same demand. Experiences from Norway show that charging stations in urban areas have a higher demand than charging stations along isolated mountain roads. Still consumers may have a higher increase in utility from an additional station at such a location than an additional station in an urban area suggesting that entry subsidies should differ between charging locations. Such asymmetries could be included in our model by assuming that different location types have different ρ 's e.g. consumers value diversity more at certain location types. Dosing the entry cost subsidy based on the mark-up on charging, as our formula prescribes, would then still make sense.

Second, we model only third party charging stations, while in reality there is one EV producer also providing high speed charging. Such an EV producer could act strategically with respect to how many charging stations to build. We have studied this case in a separate note, and find that our main result still holds even if all producers act strategically; standardization increases

welfare.¹³

Third, a higher battery capacity in EVs might mean that high-speed charging becomes less necessary. On the other hand, a well developed high-speed charging network would make a battery capacity in excess of 300 real kilometers less essential, which will make EVs cheaper to manufacture. We therefore do not believe that we can get around the need for a well developed high-speed charging network to speed up the diffusion of EVs.

Finally, we find that subsidies to EVs are superfluous. This holds if both charging of EVs and entry of charging stations are subsidized, furthermore, competition between EV suppliers is perfect, and the environmental externality of internal combustion cars is internalized. Clearly, all these conditions are rarely satisfied in real markets suggesting that subsidies to EVs should be continued. Moreover, our model is best described as depicting a static long run equilibrium, while today, the EU car market is clearly in the early stages of a transition from ICE cars to EVs. As shown by Greaker and Midttømme (2016), giving high subsidies to a clean network good may be desirable in order to facilitate a rapid transition to the new steady state.

Given that there are strict limits to public spending, one may still wonder whether higher emission cuts in the transport sector could be achieved if some of the subsidies that currently go straight to purchasers of EVs had been used for further improvement of the charging infrastructure. By giving subsidies to purchasers of EVs, we compensate them immediately for an inadequate high-speed charging network. By promising to develop the high-speed charging network faster than market developments imply, the compensation requirement could be reduced, and thereby also the need to subsidize EVs.

On the other hand, it is not certain that promises of this kind are viewed as credible. Given that increased sales of EVs are achieved by promising

¹³The author is happy to share the note upon request.

accelerated development of the charging infrastructure, it might be optimal for the authorities to lower their ambitions when the increase in sales of EVs has occurred anyway. This is frequently called the “time-inconsistency problem” in socioeconomics literature on the climate problem; see for example Golombek, Greaker and Hoel (2010).

9 Conclusion

The electroengine is superior to the combustion engine with respect to output, energy efficiency and maintenance, but most vehicles today are still driven by the internal combustion engine. Now, it looks as though the technological challenges associated with batteries are being solved, however, the end has not necessarily yet arrived for petrol and diesel cars. We have argued that the success of EVs depends in part on the establishment of an adequate high-speed charging network. Our main finding is that governments should intervene in the development of such a network.

First, policies should seek to standardize high-speed charging systems as this will unambiguously mean increased welfare. The challenges of standardization is discussed in Section 8. Second, we find that governments should subsidize both the charging at each station and the entry of charging stations. As far as we know, no government subsidizes the charging at a high speed charging location today. Around a quarter of European households live in building with more than 10 apartments where the availability of charging at home is probably limited. High-speed charging will be the only possibility for many of them to charge their EVs. Thus, the current high mark-up on the marginal cost of charging from high speed chargers could hamper the spread of EVs. If government do not want to subsidize charging, government should look into how they can convince charging companies to offer contracts that imply marginal cost pricing.

Interestingly, the rate by which the government should subsidize EV charging is exactly equal to the rate by which it should subsidize the entry costs of charging stations. Hence, in principle, the government can simply observe the mark-up on the charging price, and then calculate the optimal charging station entry subsidy.

EVs are not the only zero-emission alternative to petrol and diesel cars. Many have had, and may still have, a strong belief in hydrogen-fuelled cars. Hydrogen has the advantage that it can be stored at filling stations, so that the power requirement is not as great as for high-speed charging. Nonetheless, hydrogen cars will require a network of electrolysis stations, entailing a high investment cost. Investing in hydrogen cars alongside EVs may therefore mean a poorer network for EVs, and in a maximally undesirable scenario, both types of car may achieve little extension because of poorly developed filling and charging networks. This is clearly a topic for future research.

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Appendix

A Solving for the number of charging stations

Let ω_j denote the price on a standard charge from station j (in network i). Given that they have bought an EV, consumers maximize utility with respect to the number of charges from each of the stations in a network:

$$\max_{q_j} u_i = I - p_i - \sum_{j=1}^{M_i} \omega_j q_j + r + \kappa \left(\left(\sum_{j=1}^{M_i} (q_j)^\rho \right)^{\frac{1}{\rho}} \right)^\beta$$

The first order condition writes:

$$-\omega_j + \kappa \beta \left(\sum_{j=1}^{M_i} (q_j)^\rho \right)^{\frac{\beta-\rho}{\rho}} (q_j)^{\rho-1} = 0$$

For M_i large, the term $(\sum_{j=1}^{M_i} (q_j)^\rho)^{\frac{\beta-\rho}{\rho}}$ will be little affected by small changes in q_j . Hence, we can write the demand for charging from station j :

$$q_j = \left(\frac{\kappa \beta B}{\omega_j} \right)^{\frac{1}{1-\rho}} \quad (13)$$

where $B = (\sum_{j=1}^{M_i} (q_j)^\rho)^{\frac{\beta-\rho}{\rho}}$.

The private marginal cost of charging is $\psi(1 - \xi)$ for all stations. The charging station owners maximize profits with respect to price ω_j taking into account the downward sloping demand curve (13). We obtain for the optimal price $\omega_j^* = \psi(1 - \xi)/\rho$, and we have for q_j :

$$q_j = \left(\frac{\rho \kappa \beta (M_i)^{\frac{\beta-\rho}{\rho}}}{\psi(1 - \xi)} \right)^{\frac{1}{1-\rho}} \quad (14)$$

There is a fixed cost $f(1 - \sigma)$ of setting up a charging station where σ is a subsidy to charging station investments. Denote by y_i^e the number of consumers that is expected to have an EV of type i which can use the

charging network $j = 1, \dots, M_i$. In equilibrium each station earn zero profit, and, hence, we must have:

$$f(1 - \sigma) = y_i^e \left(\frac{\psi(1 - \xi)}{\rho} - \psi(1 - \xi) \right) q_j^*$$

\Leftrightarrow

$$q_j^* = \frac{f(1 - \sigma)\rho}{y_i^e(1 - \rho)\psi(1 - \xi)} \quad (15)$$

Hence, we can use (14) and (15) and $\beta = \rho/(2 - \rho)$ to solve for M_i :

$$M_i = \left(\frac{\rho\kappa}{2 - \rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1 - \xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \left(\frac{(1 - \rho)}{f(1 - \sigma)} \right)^2 (y_i^e)^2 \quad (16)$$

Furthermore, the money spent on charging is then given by:

$$E = \left(\frac{\rho\kappa}{2 - \rho} \right)^{\frac{2-\rho}{2(1-\rho)}} \left(\frac{\psi(1 - \xi)}{\rho} \right)^{\frac{-\rho}{2(1-\rho)}} \sqrt{M_i} \quad (17)$$

By inserting for M_i, E and q_j into the indirect utility function we can write:

$$u_i = I - p_i + r + \theta y_i^e$$

where

$$\theta = \left(\frac{\rho\kappa}{2 - \rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1 - \xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1 - \rho)^2}{f(1 - \sigma)\rho}$$

B First best policies

By inserting $\xi = 1 - \rho$ into the expression for welfare (8), we obtain:

$$W = \frac{(nx^*)^2}{2} + n(x^*)^2 + \delta nx^* - snx^* - \mu f M^*$$

It is straight forward to differentiate this expression and come up with the expressions in (9).

Then, when solving the two equations $\partial W/\partial s = \partial W/\partial \sigma = 0$, we use the following expressions:

$$\begin{aligned} M_i^* &= \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \left(\frac{(1-\rho)}{\mu f(1-\sigma)} \right)^2 (nx^*)^2 \\ \frac{\partial M_i^*}{\partial (nx^*)} &= 2 \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \left(\frac{(1-\rho)}{\mu f(1-\sigma)} \right)^2 nx^* \\ \frac{\partial M_i^*}{\partial \sigma} &= 2 \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \left(\frac{(1-\rho)}{\mu f(1-\sigma)} \right)^2 \frac{1}{(1-\sigma)} (nx^*)^2 \end{aligned}$$

$$\begin{aligned} \theta &= \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1-\rho)^2}{f(1-\sigma)\rho} \\ \frac{\partial \theta}{\partial \sigma} &= \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1-\rho)^2}{f\rho(1-\sigma)^2} \end{aligned}$$

$$\begin{aligned} x^* &= \frac{A+s-c}{n+1-\frac{\theta}{\mu}n} \\ \frac{dx^*}{ds} &= \frac{1}{n+1-\frac{\theta}{\mu}n} \\ \frac{dx^*}{d\sigma} &= \frac{(A+s-c)\frac{n}{\mu}}{\left(n+1-\frac{\theta}{\mu}n\right)^2} \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1-\rho)^2}{f\rho(1-\sigma)^2} \end{aligned}$$

The optimal σ when $\xi = 1 - \rho$, is then obtained from inserting into the following combination of the two remaining first order conditions:

$$\frac{nx^*}{n\frac{dx^*}{ds}} = \frac{\mu f \frac{\partial M^*}{\partial \sigma}}{n\frac{dx^*}{d\sigma}}$$

Moreover, the optimal s when $\rho = 0.5$ is obtained from the respective first order condition.

$$\left[nx^* + 2x^* + \delta - s - \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{ds} - nx^* = 0$$

C Second best policies

We use the expressions above in combination with the expressions in (12).

The expressions in (12) can be combined to yield:

$$\frac{nx^*}{n\frac{dx^*}{ds}} = \frac{\mu f \left(\sigma \frac{\partial M^*}{\partial \sigma} + M^* \right)}{n\frac{dx^*}{d\sigma}}$$

from which we find the optimal σ when $\xi = 0$.

Finally, the optimal s when $\rho = 0.5$ and $\xi = 0$ and $\sigma = (2 - \rho)/(2 + \rho)$ is obtained from inserting into:

$$\left[nx^* + 2x^* + \delta - s - \sigma \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{ds} - nx^* = 0$$

While the optimal s when $\rho = 0.5$ and $\xi = 1 - \rho$ and $\sigma = 0$ is obtained from inserting into:

$$\left[nx^* + 2x^* + \delta - s - \mu f \frac{\partial M^*}{\partial (nx^*)} \right] n \frac{dx^*}{ds} - nx^* = 0$$

D EV sales target

First, we solve for s as a function of σ given the sales target:

$$s(\sigma) = \Omega \left(1 + \frac{1}{n} - \frac{\theta}{\mu} \right) - A + c$$

We then insert $s(\sigma)$ into the social cost function:

$$\min_{\sigma} \left\{ \left[\Omega \left(1 + \frac{1}{n} - \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi(1-\xi)}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{2(1-\rho)^2}{\mu f(1-\sigma)\rho} \right) - A + c \right] \Omega + \sigma \left(\frac{\rho\kappa}{2-\rho} \right)^{\frac{2-\rho}{1-\rho}} \left(\frac{\psi}{\rho} \right)^{\frac{-\rho}{1-\rho}} \frac{(1-\rho)^2}{\mu f(1-\sigma)^2} \Omega^2 \right\}$$

The optimal charging station subsidy is then obtained from taking the derivative wrt. σ and setting it equal to zero. This can then be inserted into $s(\sigma)$.

E The numerical model

According to Norwegian Environment Agency (2016), the user costs of EV and ICE cars will be approximately equal in 2030. This implies that we can set $c = 0$. For the calibration we also use $\sigma = \xi = s = 0$. Moreover, we assume perfect competition such that $p = 0$.

We set the marginal cost of a charge $\psi = 3$ and ψ/ρ equal to € 6 yielding $\rho = 0.5$. For Norway, assuming a long run equilibrium with 40% EVs implies that $z = 1384434 (= nx^*)$. The three remaining parameters; κ , f and A is then found by using the following three equations:

$$El_{x,M} = \frac{\partial(nx^*)}{\partial v(M_i)} \frac{\partial v(M_i)}{\partial M_i} \frac{M_i}{nx^*} = \left(\frac{\kappa}{3} \right)^{\frac{3}{2}} \left(\frac{\psi}{\rho} \right)^{\frac{1}{2}} \frac{(M_i)^{\frac{1}{2}}}{z} \quad (18)$$

$$M_i^* = \frac{\kappa^3}{54\psi f} \frac{\rho \left(\frac{z}{\mu} \right)^2}{2f} \quad (19)$$

$$z = \frac{A + s}{1 - \frac{\theta}{\mu}} \quad (20)$$

First, we use (18) and (19) to set κ and f such that $El_{x,M}$ is either 0.01 or

0.02 and M do not turn out too high e.g. not less than 10 EVs per charging point. We settled for 12.5 in the simulations, which with 4 networks implies 50 cars per charging point not separating between networks. Then, having found values for κ and f , we can set A by (20).

Figures Charging standards

Figure 1 «The market effects of compatibility»

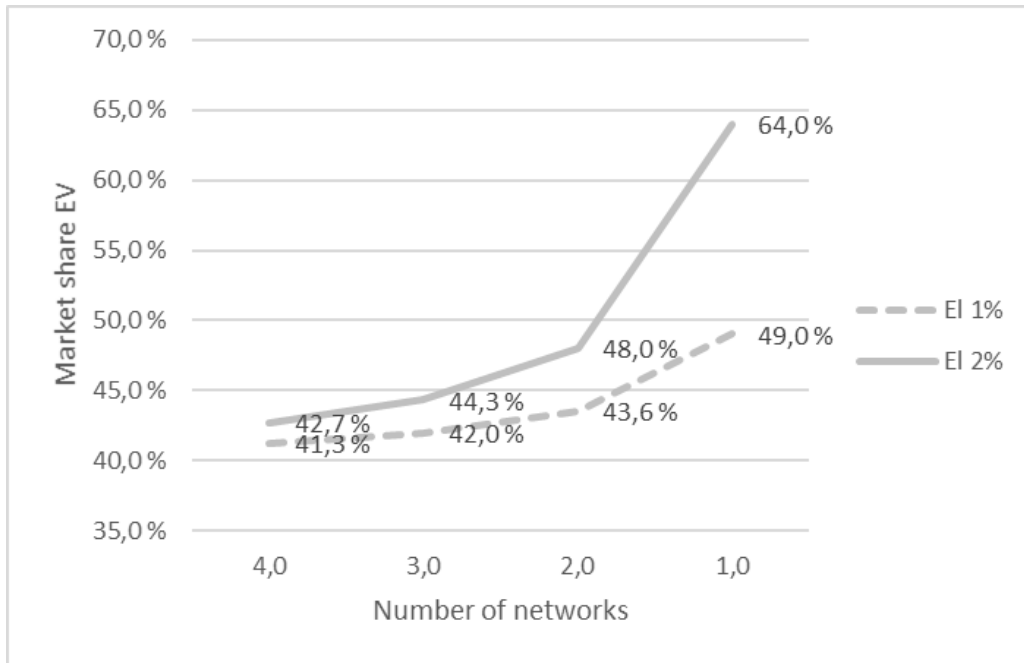


Figure 2 “EV subsidies with market share target”

