Charging of electric vehicles: Does the diversity of standards prolonge the life of the gasoline car?*

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Abstract

The organization of charging of electric cars may have a lot to say for the success of the transition to electric cars. As far as we know, this is the first paper that look at different charging standards for EVs in a theoretical model. Today, there are four standards for high-speed charging in Europe. Our basic claim is that the market diffusion of electric cars depends crucially on how the charging market is regulated. A charging network consisting of partly incompatible high-speed charging systems will unambiguously mean slower phase-in than a network in which all electric cars are compatible with all charging stations. This holds both in the case of a third party being responsible for building the charging network, and in the case the charging networks is proprietary to the EV manufactures. We also provide a numerical illustration of our theoretical findings with point of departure in the Norwegian EV market. Sales of electric cars in Norway have in recent years accounted for around 20 per cent of sales of new cars, and hence, Norway is the world champion when it comes to EV market penetration. All the same, we find that market shares could have been increased with several percentage points if charging systems had been compatible.

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1 Introduction

The electric vehicle is emerging as the number one mitigation technology for reducing green house cases from road transport. For instance, the

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IEA (2017) predicts that the EV stock will range between 9 million and 20 million by 2020 and between 40 million and 70 million by 2025 as compared to 2 million at the time of writing. Although the numbers are impressing, only the high ends of these intervals are consistent with IEA's two degree C target trajectory.

Success of the EV is dependent on further development of the battery technology increasing the energy density in batteries and lowering their production costs. According to IEA (2017) such improvements in battery technology will likely happen as long as policies continue to target the deployment of EVs. The deployment of EVs is, however, not only dependent on policies directed at the EVs. According to an increasing body of literature (see below), the extent and quality of the charging network is also major factor. In 2014 the EU adopted a directive *on the deployment of alternative fuels infrastructure*, which sets a minimum number of EV chargers per EV, and seeks to regulate the different standards being offered for both slow and fast charging of EVs.

Today, there are four standards for high-speed 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 Japanese cars. 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 charger network.

As far as we know, this is the first paper that look at different charging standards for EVs in a theoretical model. Our basic claim is that the market diffusion of electric cars depends crucially on how the charging market is regulated. A charging network consisting of partly incompatible high-speed charging systems will unambiguously mean slower phase-in than a network in which all electric cars are compatible with all charging stations. This holds both in the case of a third party being responsible for building the charging network, and in the case the charging networks is proprietary to the EV manufactures.

With respect to spurring EV adoption, Norway is among the most ambitious countries in Europe. For instance, in its National Transport Plan 2018–2019 (Norwegian Public Roads Administration, 2016) the goal is that all passenger cars sold after 2025 should be zero emission cars. Furthermore, in one of its most recent analyses, the Norwegian Environment Agency (2016) finds that the transition to electric cars for private transport is an effective and relatively low-cost climate measure, and recommends a fast conversion to electric cars for private road transport.

We provide a numerical illustration of our theoretical findings with point of departure in the Norwegian EV market. Sales of electric cars in Norway have in recent years accounted for around 20 per cent of sales of new cars, and hence, Norway is the world champion when it comes to EV market penetration. All the same, we find that market shares could have been increased with several percentage points if charging systems had been compatible.

2 Relevant literature

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 (Farrell and Klemperer, 2007). Recent research suggests that electric cars satisfy both i) and ii). The network externality is indirect, as it mainly results from a wider range of complementary goods and services. For example, Zhang et al. (2016) find from data on Norway that access to charging stations has a strong positive effect on willingness to pay for an electric car. Moreover, Li et al (2017) use date 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%. 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 electric cars. It is therefore reasonable to suppose that the utility of an electric car depends inter alia on a well-developed charging network. It is also natural to assume that the more electric cars there are, the higher the demand for charging, and hence the better developed the charging network.

The relationship between the extension of a new type of car that requires a different fuel, and the fuel network of the new car is modelled in Greaker and Heggedahl (2010). In the model the utility of the new type of car (e.g. electric car) depends on the price and supply of the new fuel (e.g. high-speed charging). However, Greaker and Heggedahl (2010) do not consider different standards for the new fuel, a factor that further complicates the picture.

The significance of charging compatibility for electric cars 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, Jing Li (2016) finds that compatibility results in more electric cars, but fewer charging stations overall. Welfare also increases substantially with full compatibility. This is consistent with the predictions emerging from our theoretical model.

Finally, Greaker and Midttømme (2016) analyses a dynamic model in which a transition from an incumbent network to the entrant network takes time. The reason is that the network goods are durable goods, and as long as they have been produced, they will stay in the market until they wear out. If the old network also 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 desireable in order to facilitate a rapid transition to the clean network good.

We cannot use the model in this paper to analyse optimal policy as the model is only static. However, given that the government wants a rapid transition to the clean network, we can analyse the effect of compatibility on the speed of transition. Moreover, we can compare the use of subsidies to the development of a charging network, with subsidies to the electric car itself. That is, in our theoretical model, we are able to separate between subsidies to EV buyers and subsidies to charging station owners.

Our point of departure is 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. Our focus is on the effect of charging compatibility on the market diffusion of EVs. We therefore expand their model in several ways; we model entry of charging stations explicitly, we include a competing product: petrol- or diesel-fuelled cars, and we calibrate the model to the EV market in Norway.

3 Organization of charging

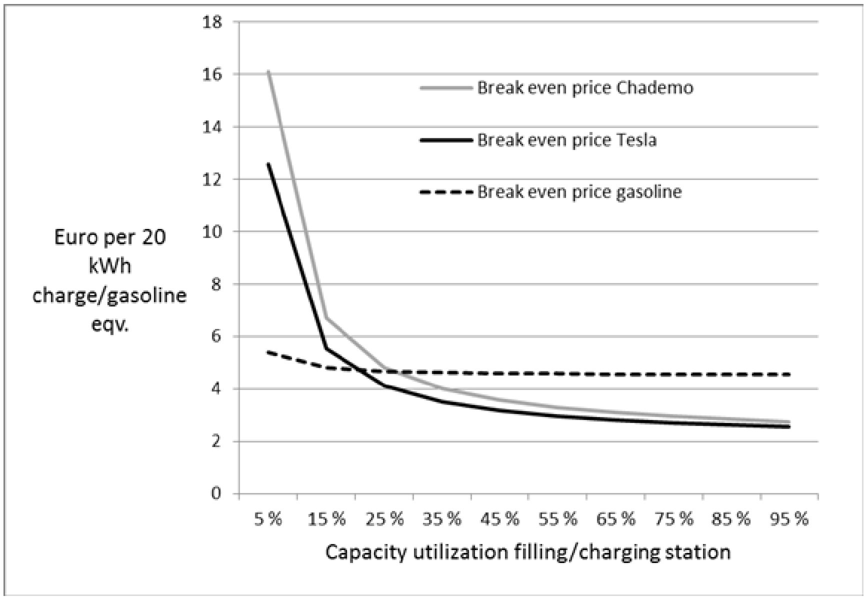
Charging can take place at different speeds depending on the effect of the charger. Chargers with an effect of 40 kilo watts (kW) or more are coined high-speed chargers. There is much to indicate that the availability of in particular high-speed charging is important for sales of electric cars; see for example Figenbaum and Kolbenstvedt (2016). It is important to most people to be able to drive long distances. The possibility of driving long distances in an electric car is naturally particularly important to people who have one car for all their needs. According to European Automobile Manufactures Association (2016), this applies to a majority of European households. Although it is primarily on long distances that the need for high-speed chargers for electric cars arises, 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.

As mentioned, there are four standards for high-speed charging in Europe. The two most widespread are Combo and Chademo, both purportedly able to charge at 50 kW. This means you can get 100 km of extra driving distance in less than half an hour. For instance, in Norway today there are 1240 charging points of this type, distributed among about 400 stations. The 400 stations are owned by various agents, the biggest being Fortum Charge and Drive and Green Contact. Many of these stations have received investment subsidies from the government. Note that a majority of stations have both Combo and Chademo available, however, according to The Institute for Transport Economics (2017) this increases the cost of a charging point significantly.

The third standard is based on AC current, and only applied to Renault Zoe, which are not able to fast charge with DC current. We do not have numbers for the availability of this fast charger type. Finally, the fourth standard is owned by Tesla Motors and is only for Tesla cars. A Tesla charger has a substantially higher capacity, and can give about 300 km extra driving distance in half an hour. Today there are 212 of these chargers in Norway, distributed among 27 stations. The German car manufacturers BMW, VW and Mercedes probably recognise that Tesla's charging system can represent a considerable competitive edge for Tesla, and are therefore planning to build their own charger network with an even higher charging rate than Tesla's - up to 350 kW, which will make it almost as fast to charge as to fill petrol.

The economy of high-speed charging is characterized by high fixed costs for the station and grid connection, but low marginal production costs in the form of power: 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 8 and 24 euro, which points to low capacity utilization. We have created a figure based on Schroeder and Traber (2012) that shows the relationship between capacity utilization at a charging station and the break-even price.

Figure 1 "The economics of fast charging"



On the y axis, we mark off the price per charging session, i.e. 100 km driving. The grey and the black solid lines give the break-even prices for different degrees of capacity utilization of the fast charger. The break-even price yields zero profit at 4 per cent return on capital. The figure also contains the break even price for a petrol pump where the price is gasoline cost per 100 km driven excluding fuel tax.

First, note that the break-even charging price decreases rapidly as capacity utilization increases towards 50 per cent. High-speed charging thus yields economies of scale. We also see that a Tesla charger will be competitive in relation to petrol (excl. fuel tax) for capacity utilization of 20 per cent already, while almost 30 per cent capacity utilization is needed for a Chademo charger. Because of its higher output, the Tesla charger can charge more cars per day, but according to Schröder and Traber (2012) does not cost correspondingly more.

Second, note that given reasonable capacity utilization, fuel costs are lower for an EV than a gasoline car even though fuels taxes are excluded and charging takes place at a fast charging point.

We cannot conclude from the figure that more EVs there are, the less charging will cost the EV owners. Due to the interaction between charging demand and charging break-even price, more EVs may lead to more charging stations and hence little change in the charging price. However, we can conjecture that, all else being equal, different standards result in poorer capacity utilization, and hence presumably a higher charging price and/or less high-speed charging stations. Finally, note that gasoline prizes are not as sensitive to utilization rate due to both lower investment costs and higher absolute capacity.

Regarding the petrol- or diesel-fuelled cars, we assume that these are not dependent on a network. There is only one standard for petrol and one standard for diesel, respectively, and since gas filling station to a large extent is sunk cost, it seems reasonable to assume that the network of petrol stations will not be substantially reduced. Moreover, as we can see from Figure 1, the break-even price on gasoline does not depend to same extent of the capacity utilization of the gasoline station.

4 The model

In the basic model set-up we have three types of economic agents; consumers, charging station owners and EV manufacturers. Consumers choose an EV or a petrol car, and if they choose an EV, they decide how much to use fast charging. Fast charging owners decide whether to enter the fast charging market, and EV manufacturers must resolve how many EVs of their type they should offer to the market. The decisons 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*.

4.1 Consumers' utility of EVs

In the period we are looking at a certain fraction of private cars will wear out and leave the car stock. Consumers owning these cars will then look for a replacement, and can choose between a standard petrol car (gasolin/diesel), or different types of EVs; each potentially compatible with only a specific charging network.

There are n EV producers, each indexed by i, which supplies x_i EVs of type i to the market. 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 follow Belleflamme and Peitz (2015), and 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.[1] Moreover, assume a representative EV owner with a given

[1] For simplicity we assume that there are no charging network present at the start

income I. The indirect utility consumers' gain from an EV can then be expressed as (with charging system i):

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

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 uniformerly distributed on $\langle -\infty, A]$, where A is the maximum a consumer is willing to pay for an electric car (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 surpress the notation i here). The parameter $\rho < 1$, indicates to what degree the different stations can substitute each other. Moreover, we impose $\beta < \rho$ to ensure that the marginal benefit of an extra charging station is declining.

5 The extent of the charging network

Let ω_j denote the price on a charge from station j. We set the marginal cost of charging to ψ for all stations. Each charging station owner maximizes profit $(\omega_j - \psi)q_j$ with respect to ω_j. As in all models of monopolistic competition with CES utility of each variety, we obtain for the optimal price $\omega_j^* = \psi/\rho$. Note that the price of charging is given independent of the number of charging stations. The interpretation is that if the number of EV owners changes, the number of charging stations adjusts such that capacity utilization stays constant. We are thus always on a certain point at the x-axis in Figure 1, and more EVs with a certain charging standard then requires more stations with that standard.

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 electric car of type i which can use the charging network $j = 1, ..., M_i$. In equilibrium each station earn zero profit, and, hence, we must have:

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

$$\Leftrightarrow$$

$$q_j^* = \frac{f(1 - \sigma)\rho}{y_i^e(1 - \rho)\psi} \equiv q \tag{2}$$

of the game. This would only add to the notation without changing the main results.

Moreover, in equilibrium total fixed and variable costs of a charging system $[f(1-\sigma)+\psi q y_i^e]\, M_i$ must equal total expenditures by all consumers using the charging system $y_i^e E$. The number of charging stations in a network is thus given:

$$M_i = \frac{y_i^e E}{f(1-\sigma)+\psi q y_i^e} = \frac{(1-\rho)E}{f(1-\sigma)} y_i^e$$

Thus, M_i is proportional to the number of EV owners being able to use network i. Inserting this into the indirect utility function (1) we obtain:

$$u_i = (I - p_i - E) + r + \kappa q^\beta \left(\frac{y_i^e(1-\rho)}{f(1-\sigma)}\right)^{\frac{\beta}{\rho}} (E)^{\frac{\beta}{\rho}}$$

which can be maximized with respect to E. The optimal E^* is:

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

Finally, we can insert E^* into the expression for M_i and the indirect utilty function (also using the expression for q). We then have for the number of charging stations on reduced form:

$$M_i^* = B\left(\frac{(1-\rho)y_i^e}{f(1-\sigma)}\right)^{\frac{\rho(1-\beta)}{\rho-\beta}}, \tag{3}$$

where $B = (\kappa\beta/\rho)^{\rho/(\rho-\beta)}(\psi/\rho)^{-\rho\beta/(\rho-\beta)}$. For the indirect utility we write:

$$u_i = I - p_i + r + v(y_i^e) \tag{4}$$

where

$$v(y_i^e) = \frac{\rho B}{\beta}\left(\frac{(1-\rho)y_i^e}{f(1-\sigma)}\right)^{\frac{\beta(1-\rho)}{\rho-\beta}}. \tag{5}$$

Thus, the individual utility function is dependent on the number of other owners of an EV with the charging system i. Note that $y_i^e = x_i$ for the case with EV firm specific standards, or $y_i^e = \sum_i x_i$ in the case of a common standard for all EV firms. Moreover, we have:

$$v'(y_i^e) = B\frac{\rho(1-\rho)}{\rho-\beta}\left(\frac{(1-\rho)}{f(1-\sigma)}\right)^{\frac{\beta(1-\rho)}{\rho-\beta}} (y_i^e)^{\frac{2\beta-\beta\rho-\rho}{\rho-\beta}} > 0$$

We assume $v''(y_i^e) < 0$, which is true as long as $\rho(1+\beta) > 2\beta$.

5.1 Demand for EVs

As a simplification, we assume that the usage of private cars is given, and that all consumers have either a petrol car or an EV. Markets with full coverage is a common assumption when studying markets with differentiated products.

Furthermore, we normalize both the willingness to pay for a petrol car and the cost of a petrol car to zero. Assuming free competition, the price on a petrol car will then also be zero. This normalization does not affect the main results of the analysis.

Since the usage of cars is given, the environmental cost of a petrol car is also given. Furthermore, since total car demand is given, it does not matter in the model whether the government chooses an environmental tax on petrol cars or an environmental subsidy to EVs.

As already stated p_i denotes the price of an electric car of type i. We let s be an environmental subsidy for buying electric cars. Then all consumers with net utility from an electric car: $r + v(y_i^e) + s - p_i \geq 0$ will buy an electric car. Since $r \sim [-\infty, A]$, we have that $A - (p_i - v(y_i^e) - s)$ consumers will buy an electric car. For given network size expectations, each electric car manufacturer will face an ordinary linear demand curve that can be expressed as follows:

$$p_i = A + v(y_i^e) + s - \sum_i x_i \tag{6}$$

where the last term is total sales of electric cars.

5.2 The EV producers

We model the EV market in each period as a static Cournot model in which the EV manufacturers have quantity as their strategic variable. However, the model differs from ordinary Cournot competition as demand for a type of electric car will depend on the expected charging network associated with this type of electric car. We set the costs of manufacture of electric cars equal to c for all n types of electric cars. The n EV manufacturers then solve the following maximization problem:

$$\max_{x_i} \left\{ \left(A + s + v(y_i^e) - \sum_i x_i - c \right) x_i \right\} \tag{7}$$

where $v(y_i^e)$ is given by (4) above.

Following Katz and Shapiro (1986), in the basic model set up, 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 electric car firm takes the production quantity of the other manufacturers as a given. The first-order condition is given thus by:

$$A + s + v(y_i^e) - \sum_i x_i - c - x_i = 0 \tag{8}$$

where $dv(y_i^e)/dx_i = 0$ by assumption.[2]

Note that since we by (8) have $x_i = p_i - c$, the profit of the EV firm π_i is equal to $(x_i)^2$. Thus, profit is strictly increasing in EV supply. We now turn to look at the market equilibrium.

6 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.

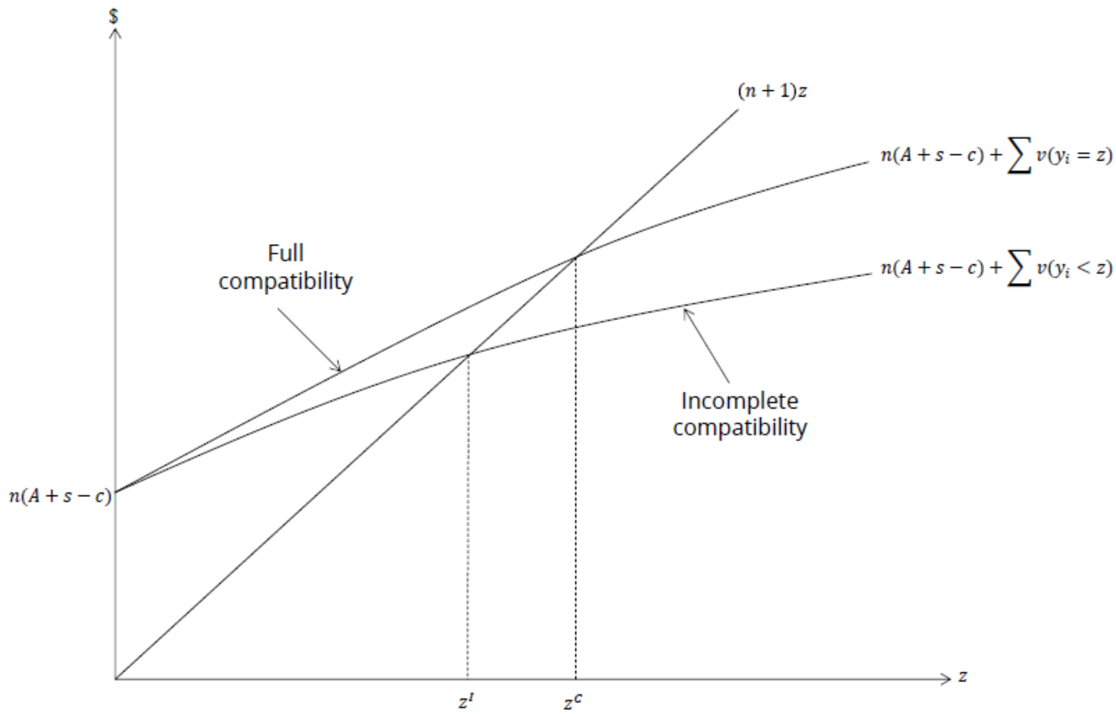
The set of equations are then relatively easy to solve as long as we assume symmetrical companies. Let $z = \sum_i x_i$. By summing the first-order conditions we then get:

$$n\,(A + s - c) + \sum_n v(y_i^e) = (n+1)z$$

Where n is the number of companies. Note that $\sum_n v(y_i^e)$ will depend on the degree of compatibility. Specifically, we must have $\sum_n v(y_i^e < z) < \sum_n v(y_i^e = z)$ since v is an increasing function. The solution can thus be expressed graphically for different degrees of compatibility. This is illustrated in Figure 2, where z represents total sales of electric cars from the n manufacturers.

Figure 2 "The fulfilled expectations equilibrium with and without compatibility"

[2] We later relax this assumption, see Section X.



The x axis indicates total sales of electric cars. We see from the figure that full compatibility will always result in the highest number of electric cars. This is because the curve that indicates full compatibility, i.e. $y_i = z$, must always be above the curve with incomplete compatibility i.e. $y_i < z$. If one electric car manufacturer elects to have an exclusive charging technology, all electric car owners will have fewer charging stations to use. This will reduce their willingness to pay, and fewer will choose electric cars.

Proposition 1 *A higher degree of compatibility, i.e. fewer, larger, charging networks will always result in more electric cars sold in equilibrium.*

Since $\pi_i = (x_i)^2$, it directly follows that in the symmetric equilibrium, compatibility leads to higher producer surplus. Thus, given that the EV manufactures could achieve compatibility costlessly, they would agree to do so. On the other hand, we should not expect that changing charging standard is costless for the electric car firms as they historically have invested in a certain system.

By insepcting the reduced form of $v(y_i^e)$, that is (4), we also have the following proposition:

Proposition 2 *Given monopolistic competition between charging stations, public sponsoring of charging networks will increase the market diffusion of EVs for all degrees of compatibility.*

The result can be seen directly from Figure 2 and (4). An increase in the subsidy, σ, will shift the $v(\cdot)$ function vertically in same way as an increase in compatibility. We will later use (4) to compare the effect of enforcing compatibility with the effect of increasing subsidies to charging stations in our calibrated model.

7 Welfare

As mentioned, we assume that total demand for cars, both electric and gasoline/diesel, in the period we are looking at is constant. Sales of petrol cars in the model are accordingly expressed as the difference between the exogenous market size and the total sales of electric cars in the period.

The individual consumer surplus from a petrol car is zero due to our normalization, while the individual consumer surplus from an EV is equal to $r_i + v(y_i^e) + s - p_i$. Inserting for p_i from the demand function (6), individual consumer surplus can alternatively be written as $r_i + z - A$ where $z = \sum_i x_i$. Only those consumers with a non-negative surplus will buy an EV e.g. $r_i > A - z$, and hence for the overall consumer surplus we have:

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

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

Let the cost of emissions per petrol car be given by γ. The cost of the charging network, apart from the public subsidy to the fixed cost of a charging station, is included in the consumer surplus through the $v(\cdot)$ function. Welfare W is then given by the following expression:

$$W = \frac{z^2}{2} + \sum_{i=1}^{n} (x_i)^2 + \gamma * z - s * z - \sigma * f * \mu * M_i \tag{9}$$

where μ is the number of separate charging networks (and μM_i is the total number of charging stations). The terms in (9) are from left to right; consumer surplus, producer surplus, the reduction in environmental damage from EV sales, the EV subsidy cost and the charging station subsidy cost.

Note that (9) only gives the per period welfare of those that change cars within a period. For those that do not change car, we have that both petrol car owners and EV owners must benefit from an increase in z. First, the level of environmental damage decreases (third term in 9). Second, the network will expand benefitting those that already have an electric car.

Clearly, the government should not aim to maximize (9) with respect to the EV subsidy s and/or the charging station subsidy σ. As analysed in Greaker and Midttømme (2016) the government will maximize the net present value of welfare over this period and *future periods* taking into account *both* those who buys a car in the period, and those who stays with their current car. With this in mind we have the following proposition:

Proposition 3 *With $\gamma + z(2+n)/n > s$ and $\sigma = 0$, a higher degree of compatibility will always increase per period welfare.*

Proof. Note first that z is increasing in the level of compatibility. In equilibrium $x_i = z/n$. With $\sigma = 0$, it is then easy to show that $\partial W/\partial z > 0$ for $\gamma + z(2+n)/n > s$. ■

Note that welfare increases in the sales of EVs even if the subsidy to EVs s exceeds the environmental costs of petrol cars γ. The reason is the indirect network effect.

8 Numerical illustration

Our theoretical model can only yield the direction of an effect, not its magnitude. In order to be able to say something more about the importance of compatibility, we have calibrated our model to Norway. The calibration must be regarded only as an illustration, as the model is very simplified: identical electric cars, no dynamics, symmetrical companies, non-strategic investing in charging stations etc. Our point of departure is that there are nine electric car companies offering EVs, and three separate charging systems (Combo, Chademo and Tesla) , but which might be "compelled" to have a common system from 2021. First we get the model to recreate the period 2012–2016. During this period, 729609 new passenger cars were registered, of which 82009 electric cars. In other words, electric cars accounted for 11 per cent of new car sales. Once the parameters have been chosen in such a way that the model succeeds in recreating the period 2012–2016, we use it to look at the period 2021–2025, with and without full high-speed charging compatibility.

In order to find a figure for the extra cost c of producing an electric car, we take Norwegian Environment Agency (2016) as our starting point. The Norwegian Environment Agency break down the costs of the transition to electric cars into infrastructure costs, production costs and inconvenience costs. For the sake of simplicity we classify cars into two categories: compact/small cars and SUV/large cars. Infrastructure costs are associated with the development of a charging network. These are the same for both categories, and constitute a small portion of overall costs. Production costs reflect the fact that it is more expensive to manufacture an electric car than a petrol-driven car of the same size and power. However, the difference is narrowing over time, partly because the price of batteries is dropping sharply. As we only have one type of car in our model, we take a weighted average of the Environment Agency's figures for compact/small cars and SUVs/large cars.

The Norwegian Environment Agency operates with an *inconvinience cost* of EVs. According to them there are four causes of inconvenience costs: i) limited range, ii) limited selection of models, iii) inadequate charging and service availability and iv) general uncertainty surrounding new technology. In our model, the inconvenience costs are represented by the sum $r + v(y_i^e)$, which denotes the willingness to pay for an EV relative to a petrol car. The value of $r+v(y_i^e)$ for the marginal consumer will depend on the market share of the electric car. There are two opposing effects: on the one hand, a higher market share will mean a better developed charging network; on the other hand, more consumers must be "persuaded" to buy electric cars, and as a result the marginal consumer will have strong preferences for petrol cars, i.e. low r.

In order to achieve a certain number of electric car sales despite the extra production and inconvenience costs, the Norwegian authorities have elected to subsidize electric cars. The subsidies largely take the form of absence of one-off registration tax, value-added tax and fuel taxes including environmental taxes; see Holtsmark and Skonhoft (2014). Moreover, based on Section 3 we set the value of f equal to Nok 100000 (fixed cost for five years), σ equal to $0,5$, $\psi = 30$ and ψ/ρ equal to Nok 45 yielding $\rho = 2/3$ (see Figure 1). Moreover, in 2016 there were a total of 1452 high-speed charging points in Norway, i.e. 0.018 per electric car. Assuming three identical charging networks, we have $y_i^e = 82009/3$. We can then calibrate β and κ from setting M_i equal to 1452/3 (number of charging stations in each network), from which we obtain $E^* = M_i^* f(1-\sigma)/(1-\rho)y_i^e$. In the following two equations β and κ are then the only unknowns:

$$M_i^* = B\left(\frac{(1-\rho)y_i^e}{f(1-\sigma)}\right)^{\frac{\rho(1-\beta)}{\rho-\beta}} \tag{10}$$

$$E^* = B\left(\frac{(1-\rho)y_i^e}{f(1-\sigma)}\right)^{\frac{\beta(1-\rho)}{\rho-\beta}} \tag{11}$$

where $B = (\kappa\beta/\rho)^{\rho/(\rho-\beta)}(\psi/\rho)^{-\rho\beta/(\rho-\beta)}$.

We also want to use the information in Li et al. (2017), we invert (10), and express the utility $v(\cdot)$ as a function of M_i:

$$y_i^e = B^{-\frac{\rho-\beta}{\rho(1-\beta)}} \left(\frac{f(1-\sigma)}{(1-\rho)}\right) (M_i^*)^{\frac{\rho-\beta}{\rho(1-\beta)}}$$

Inserting into:

$$v(y_i^e) = \frac{\rho B}{\beta} \left(\frac{(1-\rho)y_i^e}{f(1-\sigma)}\right)^{\frac{\beta(1-\rho)}{\rho-\beta}}$$

which yields:

$$v(M_i) = \frac{\rho}{\beta} B^{\frac{\rho-\beta}{\rho(1-\beta)}} (M_i^*)^{\frac{\beta(1-\rho)}{\rho(1-\beta)}}$$

We then have:

$$\frac{\Delta z}{z} = \frac{\rho}{\beta} B^{\frac{\rho-\beta}{\rho(1-\beta)}} \left[\frac{(1.1 * M_i)^{\frac{\beta(1-\rho)}{\rho(1-\beta)}} - (M_i)^{\frac{\beta(1-\rho)}{\rho(1-\beta)}}}{z}\right]$$

Finally, we calibrate A from the first order conditions when we assume 9 firms:

$$A = (10/9)z + c - s - v(y_i^e)$$

Our calibration implies that if the fast charging network increases with a new station, consumers are willing to pay:

$$v'(M_i) = \frac{\beta(1-\rho)}{(\rho-\beta)(1-\beta)} B^{\frac{\rho-\beta}{\rho(1-\beta)}} (M_i^*)^{\frac{\beta-\rho}{\rho(1-\beta)}},$$

that, is, Nok more for an EV. This could be compared with existing estimates of consumers' willingness to pay for extra milage: Daziano (2013) and Hidrue et al. (2011) find, using different methods, that willingness to pay for 10 km extra driving distance is between Nok 1300 and Nok 3900. Hence, one could say that we, with respect to increased willingness to pay for an EV, equate y charging stations with 10 km extra driving distance.

The Environment Agency (2016) anticipates a substantial reduction in inconvenience costs leading up to the period 2021–2025. This can be implemented in the model as an increase in A. Specifically, we let A increase, so that we get a 40% market share for electric cars in the period 2021–2025 with three incompatible charging networks. Table 1 presents a list of the most important parameters:

Table 1 "Parameter values"

Parameters	2012-2016 (Nok)	2021-2025 (Nok)
s	128037	97524
c	79550	49037
Ψ/ρ	45	45
σ	0,5	0,5
f	100000	100000
A	40421	247756

Then in Table 2, we show the results of four simulations focusing on the market share of EVs:

Table 2 “The significance of compatibility in the period 2012–2025”

	Base case ρ = 2/3	Alternative ρ = 1/2
Market share 2021-2025 Three networks	40%	40%
Market share 2021-2025 Two networks	41%	44%
Market share 2021-2025 One network	42%	68%
Share 2021-2025 42% Three networks, σ = 0,8	Cost of charging subsidy NOK 881 mill.	
Share 2021-2025 42% Three networks, Δs = 16214	Cost of EV subsidy NOK 5971 mill.	

In all the runs, we reduce the subsidy in pace with the reduction in production costs. The effect of making the charging networks compatible is more dramatic the lower the ρ as expected. It is important to remember that the socioeconomic cost of phasing in electric cars is not equal to the amount of the subsidy multiplied by the number of electric cars. All those except the marginal consumer who buy an electric car obtain a utility gain from the electric car compared to a petrol car. This gain is maximized when there is full compatibility. The amount of the subsidy also has to be subtracted in order to arrive at the socioeconomic cost.

9 Theoretical extensions

So far we have assumed that a third party builds the charging network. This is only parly what we see today; there are independent companies developing fast charging networks, but we also have the Tesla EV company, which has invested in its own network. In the extension section we look at the latter case. Note first that all the above results would follow if for instance the car companies followed a rule saying that for each (1000) car sold they should invest in a certain number of charging stations. As we can see from (**??**) this is the reduced form of the monopolistic competition model. On the other hand, the above results assumed symmetric companies, which as explained in Section 3 is not the case for the charging networks we see today.

9.1 Asymmetric companies

The Tesla company has developed a superior fast charging network, and in this extension we will look at the effect of asymmetric network benefits. For simplicity we look at only two firms, and a linear $v(\cdot)$ function equal to $a_i y_i^e$, $i = 1, 2$ where $a_1 > a_2$.

In the case with two separate networks, firm i maximizes:

$$\pi_i = (A + s + \alpha_i y_i^e - x_i - x_j - c)\, x_i$$

where $\alpha_i < 1$, $i = 1, 2$. The first order conditions are:

$$A + s + \alpha_i y_i^e - 2x_i - x_j - c = 0$$

Assuming a fulfilled expectations equilibrium, we obtain for the optimal supply of the two types of EVs:

$$\begin{aligned} x_1 &= \frac{(A - c + s)(1 - \alpha_2)}{3 - 2\alpha_1 - 2\alpha_2 + \alpha_1\alpha_2} \\ x_2 &= \frac{(A - c + s)(1 - \alpha_1)}{3 - 2\alpha_1 - 2\alpha_2 + \alpha_1\alpha_2} \end{aligned}$$

where $\alpha_1 > \alpha_2$. It can be shown that profits are equal to:

$$\begin{aligned} \pi_1 &= \left(\frac{(A - c + s)(1 - \alpha_2)}{3 - 2\alpha_1 - 2\alpha_2 + \alpha_1\alpha_2} \right)^2 \\ \pi_2 &= \left(\frac{(A - c + s)(1 - \alpha_1)}{3 - 2\alpha_1 - 2\alpha_2 + \alpha_1\alpha_2} \right)^2 \end{aligned} \tag{12}$$

In the full compatibility equilibrium, we assume that the network benefit for both firms are $(\alpha_1 + \alpha_2)(y_1^e + y_2^e)/2$. Moreover, due to equal costs we will have $x_1 = x_2$ in equilibrium. The profit expressions of the two firms then write:

$$\pi_1 = (A + s + (\alpha_1 + \alpha_2)(y_1^e + y_2^e)/2 - x_1 - x_2 - c)\, x_1$$

And we have for profit and output:

$$\begin{aligned} x_1 = x_2 &= \frac{A - c + s}{3 - \alpha_1 - \alpha_2} \\ \pi_1 = \pi_2 &= \left(\frac{A - c + s}{3 - \alpha_1 - \alpha_2}\right)^2 \end{aligned} \tag{13}$$

By comparing (12) and (**??**), we find that firm 1 will only accept compatibility if:

$$2\alpha_1 - (\alpha_1)^2 \geq \alpha_2$$

which much be the case since $a_1, \alpha_2 < 1$, and $\alpha_1 > \alpha_2$.

Proposition 4 *Given linear network benefit functions; if one firm has a superior network, the superior firm will loose profit on making its network compatible with the inferior firm.*

Thus, even if making the charging systems compatible is costless, we should not *a priori* expect to see EV firms entering freely into compatibility as long as one of the firms has a superior network.

10 Strategic investing in charging infrastructure

A key assumption in Figure 2 is that companies take consumer expectations as given when they fix quantity (and hence the charging network). In this section we will look at the case in which firms are able to influence consumers expectations about the future charging network by investing in a higher production capacity, and hence, committing to build a larger network for their EV type.

Electric car manufacturers still solve the following maximization problem:

$$\max \left\{ \left(A + s + v(y_i^e) - \sum_i x_i - c \right) x_i \right\}$$

However, the first-order condition is given by:

$$A + s + v(y_i^e) + v' \frac{dy_i^e}{dx_i} x_i - \sum_i x_i - c - x_i = 0 \tag{14}$$

that is, the fourth term in (14) is not in (8) above. By the term $v'x_i dy_i^e/dx_i$ the EV firm takes into consideration that its level of production (capacity choice) will affect consumers expectations about the firm's future charging network.

Adding the n first-order conditions, and assuming $dy_i^e/dx_i = 1$ and $x_1 = x_2 = ... = x_n$ (symmetry), we have:

$$n\,(A + s - c) + \sum_n v(y_i^e) = (n + 1 - v'(y_i^e))z \tag{15}$$

where $z = \sum_i x_i$. Thus, we see that the effect of strategic investing is that straight line in Figure 2 pivots downward (due to the positive term $v'(y_i^e)$) leading to a higher z for all degrees of compatibility, and hence also, a higher market share for EVs. The size of the downward shift is, however, dependent of the degree of compatibility as $v''(y_i^e) < 0$. Thus, with strategic investing in networks on the firm level, it is no longer as obvious that enforcing compatibility will increase the market diffusion of EVs. With full compatibility the term $v'(y_i^e)$ will be smaller in value, since the firm only adds to the network created by the other firms instead of building its own network from scratch.

Denote the solution to (15) with *complete incompatibility* x^{NC} and total EV sales in this case z^{NC}. Moreover, denote the solution to (15), *if firms' networks were compatible*, x^C and total EV sales in this case z^C. In order to know whether z^C is greater than z^{NC}, we must evaluate the following inequality:

$$nv(z^C) + v'(z^C)z^C \lesseqgtr nv(x^{NC}) + v'(x^{NC})z^{NC} \tag{16}$$

where the left hand side refers to the full compatibility case, and the right hand side is the case with complete incompatibility. We have $nv(z^C) > nv(x^{NC})$ while $v'(z^C) < v'(x^{NC})$. Divide both sides by n, and observe that for $n = 1$ we must have:

$$v(nx^C) + v'(nx^C)x^C = v(x^{NC}) + v'(x^{NC})x^{NC}$$

since then $x^C = x^{NC}$.

We then take the derivative of the left hand side with respect to n assuming that $x^C = x^{NC}$:

$$\frac{\partial\left(v(nx^{NC}) + v'(nx^{NC})x^{NC}\right)}{\partial n} = \left[v'(z^{NC}) + v''(z^{NC})x^{NC}\right]x^{NC} \tag{17}$$

This derivative is clearly positive as long as $v'(x) + v''(x)x \geq 0$, which for example holds for $v = (y_i^e)^\gamma$, $0 < \gamma < 1$, and $v = \ln(y_i^e)$.[3] Hence, we have the following proposition:

Proposition 5 *Even with strategic investing in charging infrastructure, full compatibility will result in more electric cars sold in equilibrium than no compatibility as long as $v(\cdot)$ satisfies $v'(x) + v''(x)x \geq 0$.*

In our opinion strategic investing is less likely if a third party is responsible for the charging network.

11 Private incentives to promote compatibility

If it is easy to make the charging technologies compatible, the overall profit of the electric car industry also increases in our model (as long as no firm has a superior charging technology). One could therefore expect them to coordinate amongst themselves, and promote a common 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 electric cars. As we understand it, the new 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. Above we examined this in more detail by expanding the model of Katz and Shapiro to apply to a situation with two manufacturers, one of them having a better charging technology than the other. Our main finding was that even when discounting the costs of creating a common standard, the manufacturer with the superior charging system prefers incompatibility. Again, this applies even if the industry and society as a whole would benefit from a compatible solution.

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,

[3] The condition $v'(x) + v''(x)x \geq 0$ is harder to meet than $v'(x) + v''(x)x' \geq 0$, with $x' < x$, which is the case in (17).

but technical differences among cars may make this more difficult in the future. Standard-setting organizations are usually based on consensual decisions, which may be difficult to achieve when one of the participants has gained a head start. In the current phase, it looks as though electric car suppliers may be choosing a strategy that involves developing separate solutions. We are then left with what Farrell and Simcoe (2011) call the "dictator" solution, where the authorities, for example, set a 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 makes of electric cars, and it is likely difficult for the EU to achieve full standardization without this also taking place in the rest of the "world". Patents can also prevent the "dictator" solution.

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.

12 Discussion and conclusion

As early as in 1838, Moritz Hermann von Jacobi succeeded in building an electric, battery-driven boat that transported people across the Neva River in St. Petersburg. It was not until 20 years later that Nikolaus August Otto designed the first combustion engine. The electroengine is superior to the combustion engine with respect to output, energy efficiency, maintenance etc., but most vehicles are still driven by Otto's invention today. Now it looks as though the technological challenges associated with batteries are being solved, at least when it comes to passenger cars. However, the end has not necessarily arrived yet for petrol and diesel cars. We have assumed that the success of electric cars depends in part on the establishment of an adequate high-speed charging network. This means that the existence of many different standards could brake the introduction of electric cars in the EU.

If we disregard the households that do not have the possibility of charging cars at home, a higher battery capacity in electric cars should 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 electric cars cheaper to manufacture. We therefore do not believe that we can get around the need for a well developed high-speed charging network. Another factor is that adaptors that make it easier to switch between the different charging systems may be developed. These adaptors will come at a price and occupy space in the car nonetheless, which still makes compatibility desirable.

One means of preventing the emergence of too many different standards is to continue investment subsidies for the building of charging stations that must be available to all makes of car. One challenge presented by this type of measure is keeping up with technological developments. The chargers that receive financial support in for instance Norway today have a capacity that is less than half of that offered to its customers by Tesla. This past year news has also been received that several major manufacturers are developing faster charging technology. We mentioned that prominent carmakers such as BMW, Ford, VW and Mercedes have launched plans for a new, faster charging network. To facilitate the upgrading of the publicly sponsored high-speed charging stations, investment subsidies should be allocated on the condition that the stations are ready, or at least dimensioned, for more power-intensive charging. There is probably also a need to regularly review the scope and geographical orientation of the measure. For example, high-speed charging stations should probably be established for households in apartments where there is limited opportunity to charge cars at home.

Another question is whether the power supply in the EU is compatible with rapid and widespread introduction of electric cars. Skotland et al. (2016) are looking at this for Norway, taking as their point of departure a scenario with 1.5 million electric cars in 2030 (more than 50% of the stock). The expected power consumption of these cars will not represent a problem; it does not account for more than 3% of today's power consumption. However, many high-speed chargers operating together might pose a challenge for transformers and cables in some local distribution networks. According to Skotland et al. (2016) much of this equipment will have to be replaced regardless by 2030, which will make capacity upgrading possible without major extra costs.

There are several projections for what it will cost to cut CO2 emissions by phasing electric cars into private transport. For example, for

Norway, Holtsmark and Skonhoft (2014) appears to find far higher figures for the cost per tonne of CO2 cuts than Environment Agency (2016). However, the costs associated with electric car policy have not been the subject of this article. The ambitious phase-in of electric cars in Environment Agency (2016) must be viewed in light of the Paris Agreement on reduction of greenhouse gas emissions. Pursuant to this agreement, Norway appears likely to be required to make a 40 per cent reduction in the non-ETS sector. Given the relatively short time remaining until 2030, this is a very ambitious goal also taking into consideration that the EU is planning a scheme for trading of cuts in non-ETS emissions among EU/EEA countries. To date no institutions have been established to organize and monitor this trading. Moreover, there is great uncertainty as to what prices Norway can expect to pay for non-ETS emission reductions in other EU countries. Analyses by Aune and Fæhn (2016) suggest that these may be around NOK 2000/tonne CO2. In this article we therefore assume that Norwegian authorities will carry out substantial phase-in of electric cars in the period up to 2030.

One may wonder whether emission cuts in the transport sector could be achieved more reasonably if some of the subsidies that currently go straight to purchasers of electric cars had been used for further improvement of the charging infrastructure. By giving subsidies to purchasers of electric cars, 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 electric cars. On the other hand, it is not certain that promises of this kind are viewed as credible. Given that increased sales of electric cars are achieved by promising accelerated development of the charging infrastructure, it might be optimal for the authorities to lower their ambitions when the increase in sales of electric cars 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).

Compatibility and charging do not apply only to electric cars, but are also a topic in connection with shore-side electricity to the cruise ship industry. The already mentioned EU Directive of 2014 requires that all major harbours in Europe must be able to supply shore-side electricity by 2025. This has created debate and competition around charging systems, much in the same way as in the electric car industry. There is a European standard, but both Norway's coastal steamer and Color Line have chosen not to implement it. This means that many Norwegian harbours have to install at least two different chargers.

Electric cars 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 electric cars may therefore mean a poorer network for electric cars, and in a maximally undesirable scenario, both types of car may achieve little extension because of poorly developed filling and charging networks. This is also something the authorities should think about; should they invest all their efforts in electric cars, or should they go in for developing two parallel networks that can never be compatible?

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