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The tradeoff between indirect network effects and product differentiation in a decarbonized transport market*

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Abstract

What factors determine whether it is optimal with one or more technologies in a decarbonized road transport sector, and what policies should governments choose? We investigate these questions theoretically and numerically through a static, partial equilibrium model for the road transport market. We find that two important factors that determine whether it will be and whether it should be one or more technologies are how close substitutes the two vehicle technologies are and the number of vehicles of the other technology. Our numerical results indicate that with two incompatible networks, two differentiated goods are optimal compared to only one if they are not too close substitutes. The first-best policy is a subsidy of the markup on charging and filling, where the markup is higher the higher the increased utility of more stations. In addition, to avoid an unwanted lock-in, a temporary stimulus may be needed to reach the stable equilibrium.

JEL: H23, L14, L91 and Q58

Keywords: Indirect network effects; Decarbonization; Climate policy; Electric vehicles; Hydrogen vehicles.

1 Introduction

Limiting global warming to well below 2°C and aiming at 1.5°C, in line with the Paris agreement, would require rapid and far-reaching transitions in all sectors, including the transport sector (IPCC, 2018). The European Commission has proposed that the EU should have net-zero emissions by 2050, and the average share of non-fossil-fuelled cars in their 2050 scenarios is 96% (European Commission, 2018). Many countries, including China, Great Britain, France and Norway have decided to stop sales of gasoline and diesel cars some time between 2025 and 2040 (Burch & Gilchrist, 2018). Policies in some of the most climate-ambitious regions in the world, such as the EU and California, promote both fast charging stations for electric vehicles and hydrogen stations (European Commission, 2016, 2018; CARB, n.d.). However, there is limited scientific knowledge about whether it is optimal with one or more technologies in a decarbonized road transport market, and what policies governments should choose.

To have more than one technology in the transport sector gives the consumer more variety in which type of vehicle to choose. Two alternatives are better than one. For instance, electric vehicles are more energy-efficient and thus cheaper to use than hydrogen vehicles, whereas hydrogen vehicles can refuel faster than

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batteries can be charged. The benefit of product differentiation therefore points in direction of at least two technologies. This is especially the case when we think of the whole road transport sector, not just the passenger cars, and interpret "consumers" as all road transport users, including commercial and public agents using trucks, buses etc. On the other hand, the utility from the network of stations increases the more stations there are with the same technology. Thus, the indirect network effects in the transport sector point in direction of only one technology, because for the consumer, one larger network is better than two smaller. How to balance the trade-off between the indirect network effects and the benefit of product differentiation? This article investigates what factors determine how many technologies that are optimal in a decarbonized road transport market, what the market outcome will be, and what policies governments should choose.

We analyze these questions theoretically and numerically through a static, partial equilibrium model. Dynamic investigations of the transition phase are of course important, and for instance Greaker and Midttømme (2016) and Zhou and Li (2018) find that there can be excess inertia in the transition from fossil-fuelled vehicles to non-fossil-fuelled vehicle. However, a static model has the advantage of making equilibria analysis more tractable. Hence, this article is not about how to achieve an optimal *transition* from fossil-fuelled to non-fossil-fuelled vehicles, but rather about what we should be *transitioning to.* In a 100% decarbonized transport sector there will be no room for fossil-fuelled vehicles, and therefore they are not included in our analysis.

We find that important factors, both for the optimal solution and the market outcome, are how close substitutes the two vehicle technologies are, the net utility of the vehicle itself and of charging/filling, and the fixed cost of the stations. Furthermore, the market outcome for one particular technology depends crucially on the number of vehicles of the other technology, and critical mass may be needed to pass an unstable equilibrium. This means that if one technology has gotten a head, the other technology might not be able to enter into the market, even if it is optimal to have two technologies. Further, the likelihood of entry is higher the higher is the utility of the first few vehicles. The numerical results, based on a calibration to the Norwegian road transport sector, indicate that a combination of the two technologies is optimal, even when they are close substitutes. The welfare of having two technologies decreases the closer substitutes the two technologies are, and if they are sufficiently close substitutes, welfare is highest with only one technology.

Further, we find that the first-best policy is simply a subsidy of the monopoly markup on charging/filling. In our model, the monopoly markup increases with the consumers' utility from more stations. The higher the utility of more stations, the higher the network externality, and hence the higher is the optimal subsidy to correct for this externality. The result that the preference for variety in the complementary product is important for determining the network externality is in line with the result in Church, Gandal, and Krause (2008). In addition, due to the possibility of unstable equilibria, a temporary stimulus may be needed to reach the stable equilibrium and avoid an unwanted lock-in.

In contrast to network effects that are directly linked to the primary product (for instance the vehicle), the indirect network effects mean that the utility of the consumer increases through increased supply of the complementary product such as stations (Greaker & Midttømme, 2016). In a review article about network effects, Katz and Shapiro (1994, p.105-106) state that for *direct* network effects there are at least two important features. First, it is a "tendency of one system to pull away from its rivals in popularity once it has gained an initial edge." Second, "[c]onsumer heterogeneity and product differentiation tend to limit tipping and sustain multiple networks."[1] This is exactly what we find in a model with *indirect* network effects. The first contribution of our paper is thus to establish that the conclusion in Katz and Shapiro (1994) for direct network effects carries over to indirect network effects.

As opposed to most models on network effects (for instance Katz and Shapiro (1985), Belleflamme and Peitz

[1] Katz and Shapiro (1994) build on the findings in e.g. Katz and Shapiro (1985), Farrell and Saloner (1986a) and Farrell and Saloner (1986b).

(2015) and Greaker and Midttømme (2016)), the total size of the market for the primary product (vehicles) is endogenous in our model, meaning that there is no such thing as a "fully covered market". This makes the analysis richer compared to models where the market size is fixed, and is hence a contribution to the literature on network effects.

Most previous research on indirect network effects assume from the outset that there is either one or two network, without analyzing whether there will or should be one or two. Greaker and Midttømme (2016) and Greaker and Heggedal (2010) investigate whether there are excess inertia or lock-in in the transition to a clean network good and per assumption divide the market between one clean and one dirty network good. Conrad (2006) investigates the choices of quality and pricing policies when the market consists of either one or two network goods, but does not characterize when the market outcome will be one or two technologies.

To our knowledge this is the first model of indirect network effects with two competing, incompatible goods where the division of the market between the goods *and* the total size of the market is endogenous. The latter feature is particularly important in the context of our policy question, namely whether governments should support one or two technologies in a fully decarbonized road transport sector, as the answer to this partly depends on the total size of the market. To our knowledge no previous studies have analyzed this question using a model with network effects.

We find that it is optimal to subsidize the monopoly markup on the *complementary* product (the stations), because it leads to the price of the complementary product being equal to the marginal cost. This policy proposal is in line with a statement in the review paper by Katz and Shapiro (1994), but to our knowledge it has not been demonstrated analytically before.

The rest of the paper is organized as follows. In the next section, we present the model, characterize the market solution, and analyze the possibility of zero, one or two market equilibria. Then, in section 3 we derive the optimal solution, compare with the market outcome, and derive the first-best policy. Further, in section 4 we calibrate the model, and perform a variety of simulations, before we conclude and discuss limitations in the final section.

2 Modelling the road transport market

2.1 The model

2.1.1 Assumptions in the model

We develop a partial equilibrium model of the road transport market. Two imperfect substitutes (vehicles) that are part of two incompatible networks (stations) are modeled. We will refer to the two technologies as electric (1) and hydrogen (2) vehicles. The insights from our analysis easily carries over to a situation with three or more technologies. The analytical model is quite general, and may be applied also in other sectors than the road market.

As we want to focus on network externalities in this paper, other externalities such as environmental and knowledge externalities are not incorporated in our model. Obviously, the main reason for the shift to non-fossil fuelled vehicles is the climate change problem. However, for the long-term choice between such vehicles and their network this is of limited importance as there are no direct greenhouse gas emissions from such vehicles, and because electricity is likely to become more or less decarbonized in the future. Effects on local air pollution will also be quite similar for electric and hydrogen vehicles, but probably different for biofuels.

In the model, there are two types of economic agents; a representative consumer (representing both consumers and firms that buy and use vehicles) and firms that supply the network of stations. Both types of agents are assumed to maximize their surplus. We use a representative consumer approach, where this consumer represents all types of road transport. Since the representative consumer represents all consumers in aggregate, it will likely have a large number of vehicles, possibly of both technologies. Heterogeneous preferences for the two technologies are captured through modelling them as imperfect substitutes in the representative consumer's utility function. The indirect network effect is modelled through the utility of the consumer being dependent on how many stations there are. However, the representative consumer treats the number of stations as exogenous, and hence does not take into account that increased number of vehicles leads to increased number of stations. Therefore, the representative consumer does not internalize the indirect network effects.

We do not model the market for vehicles, but rather assume exogenous vehicle prices. This is reasonable for a country that is mostly importing vehicles. We assume that there is only one vehicle model of each technology. This means that we disregard the fact that there are different segments of the vehicle market, and that there are different varieties and sizes of each type of vehicle, as we want to focus on the choice between two technologies. This also means that we assume that all vehicles types can charge/fill at the same station. At least for hydrogen this seems to be the case (E24, 2019a). Note that when we refer to demand for vehicles, we do *not* refer to sales in a given period but to the number of vehicles in the long-run equilibrium (i.e., the stock of vehicles).

Infrastructure owners decide which infrastructure to build; hydrogen stations or fast charging stations. We assume monopolistic competition in the station market. The stations ij providing a certain energy input i are heterogeneous as each station is spatially differentiated to the other stations. Further, due to free entry in monopolistic competition the station market is characterized by zero profits in equilibrium. It then follows that if the number of vehicles with technology i changes, the number of stations adjusts such that capacity utilization stays constant.

2.1.2 Consumer's utility of vehicles

The utility of the representative consumer is assumed to depend linearly on the composite good y. In addition, it depends on two additively separable vehicle-related benefits. The first of these is the benefit of the vehicles themselves (x_i), where utility is quadratic in vehicle demand with decreasing marginal utility. Moreover, the marginal utility of vehicles of technology i depends negatively on the number of vehicles of the other technology $-i$. The second vehicle-related benefits are the benefits of charging/filling, which depend on the number of stations (M_i) and charging/filling per station (q_{ij}).[2] The utility of the representative consumer is:

$$u(y, x_i, q_{ij}) = y + \sum_{i=1}^{2} a_i x_i - 1/2(b_1 x_1^2 + 2\phi x_1 x_2 + b_2 x_2^2) + \sum_{i=1}^{2} \left(x_i \kappa_i (\sum_{j=1}^{M_i} q_{ij}^{\rho_i})^{\frac{\beta_i}{\rho_i}} \right) \tag{1}$$

where a_i is the utility of the first vehicle, b_i is a parameter that determines the price sensitivity of demand for vehicles, ϕ is the substitutability between the vehicle technologies, κ_i is the utility of the charging/filling and therefore determines the magnitude of the indirect network effect, ρ_i is the utility from more stations (i.e. to what extent the stations can substitute each other), and β_i is the indirect utility from more stations via total number of charges/fillings per vehicle.

Seeing the representative consumer as the society as a whole (and leaving environmental externalities out), the utility of the consumer increases when there are more vehicles, more stations, and more charging/filling.

[2]This second part of the utility function is taken from Greaker (2019), which again is based on Belleflamme and Peitz (2015), which again builds on Dixit and Stiglitz (1977).

The consumer maximizes its utility $u(y, x_i, q_{ij})$ constrained by a binding budget constraint:

$$I = y + \sum_{i=1}^{2}\left(p_i(1-u_i)x_i + x_i\sum_{j=1}^{M_i}(\omega_{ij}(1-s_i)q_{ij})\right) \tag{2}$$

where I is exogenous income for the representative consumer, p_i is the exogenous (periodical) price of vehicle i, u_i is a potential subsidy of the vehicle, ω_{ij} is the seller price of charging/filling at station ij, and s_i are potential ad valorem subsidies of charging and filling.

In order to get a tractable analytical solution, we assume that stations of a certain technology i are symmetric:

$$q_{ij} \equiv q_i$$

When combining equations (1) and (2), we then get:

$$u(x_i, q_i) = I - \sum_{i=1}^{2}\left(p_i(1-u_i)x_i + x_iM_i\omega_i(1-s_i)q_i\right) + \sum_{i=1}^{2} a_ix_i - 1/2(b_1x_1^2 + 2\phi x_1x_2 + b_2x_2^2) + \sum_{i=1}^{2}\left(x_i\kappa_iM_i^{\frac{\beta_i}{\rho_i}}q_i^{\beta_i}\right) \tag{3}$$

The representative consumer optimizes its utility with respect to number of electric vehicles, hydrogen vehicles, charging and filling (and not with respect to the number of stations). We assume interior solution for the variables we optimize, but the equations hold whether or not the other technology is used. By differentiating equation (3) with respect to x_i and setting equal to zero, we find the following expression for the number of vehicles:

$$x_i(M_i, q_i, x_-i) = \frac{1}{b_i}\left(a_i - \phi x_{-i} + \kappa_iM_i^{\frac{\beta_i}{\rho_i}}q_i^{\beta_i} - p_i(1-u_i) - M_i\omega_i(1-s_i)q_i\right) \tag{4}$$

By differentiating equation (3) with respect to q_i (strictly speaking with respect to q_{ij}) and setting equal to zero, we find the following expression for charging/filling[3]:

$$q_i(M_i) = M_i^{-\frac{\rho_i-\beta_i}{\rho_i(1-\beta_i)}}\left(\frac{\kappa_i\beta_i}{\omega_i(1-s_i)}\right)^{\frac{1}{1-\beta_i}} \tag{5}$$

Inserting for q_i into (4) we can derive an expression for x_i as a function of x_{-i} and M_i (and exogenous parameters):

$$x_i(M_i, x_{-i}) = \frac{1}{b_i}\left(a_i - \phi x_{-i} - p_i(1-u_i) + M_i^{\frac{\beta_i(1-\rho_i)}{\rho_i(1-\beta_i)}}(\omega_i(1-s_i))^{\frac{-\beta_i}{1-\beta_i}}\kappa_i^{\frac{1}{1-\beta_i}}\beta_i^{\frac{\beta_i}{1-\beta_i}}(1-\beta_i)\right) \tag{6}$$

From (5) we notice that charging/filling at each station decreases in the price, but also in the number of stations. Total charging/filling per vehicle (q_iM_i) increases in M_i, however. From (6) we see that the stock of vehicle of technology i depends positively on the number of stations available for this technology, but negatively on the price of both buying a vehicle and charging/filling, as well as on the number vehicles of the other type.

[3]This expression implies that the price elasticity of demand for charging/filling is $\frac{-1}{1-\beta_i}$. When $\beta_i > 0$, it means that the price elasticity (absolute value) is larger than 1, which is a quite high elasticity. Most studies on long-run price elasticity of demand for gasoline is between 0.5 and 1, see for instance Labandeira, Labeaga, and López-Otero (2017) and Yatchew and No (2001).

2.1.3 The station network

Each station owner maximizes profit $x_i(\omega_{ij} - \psi_{ij})q_{ij}$ with respect to ω_{ij}, taking into account that q_{ij} depends on ω_{ij}, where $\psi_{ij} = \psi_i$ is the unit cost of charging/filling. It is straightforward to show that the optimal price for the station owner then is $\omega_{ij} = \omega_i = \psi_i/\rho_i$, so that the monopoly markup is $\frac{1}{\rho_i}$.[4] If the government wants to correct the market failure of monopoly pricing, it could subsidize the monopoly markup. The subsidy that corrects for the markup is found by setting the consumer price equal to the marginal (unit) cost:

$$\omega_i(1 - s_i) = \psi_i \Leftrightarrow s_i = 1 - \frac{\psi_i}{\omega_i} = 1 - \rho_i \tag{7}$$

There is a fixed cost f_i of setting up a station. We allow for a government ad valorem subsidy σ_i to investments in stations, so that the station owner only pays $f_i(1 - \sigma_i)$. In equilibrium, due to free entry we assume that each station owner earns zero profit, meaning that total fixed and variable costs must equal total payments for charging/filling from the representative consumer:

$$f_i(1 - \sigma_i) = x_i(\omega_i - \psi_i)q_i \tag{8}$$

We then insert for the consumer's optimal charging/filling q_i in (5) into (8), replace ω_i with ψ_i/ρ_i, to get the following expression for M_i:

$$M_i(x_i) = \left(\frac{x_i}{f_i(1 - \sigma_i)}\right)^{\frac{\rho_i(1-\beta_i)}{\rho_i-\beta_i}} (1 - s_i)^{\frac{-\rho_i}{\rho_i-\beta_i}} \psi_i^{\frac{-\rho_i\beta_i}{\rho_i-\beta_i}} (\kappa_i\beta_i)^{\frac{\rho_i}{\rho_i-\beta_i}} \rho_i^{\frac{\rho_i\beta_i}{\rho_i-\beta_i}} (1 - \rho_i)^{\frac{\rho_i(1-\beta_i)}{\rho_i-\beta_i}} \tag{9}$$

We see that the number of stations of technology i in equilibrium increases with the number of vehicles with technology i, and also with the two types of subsidies σ_i and s_i, whereas higher fixed (f_i) and variable (ψ_i) costs reduce the number of stations. In general, it is not possible to express x_i on reduced form.[5]

2.2 The existence and the number of equilibria

In the previous subsection, we assumed that a market equilibrium exists, and derived conditions that must hold in equilibrium. In this subsection we examine under what conditions an equilibrium exists, and whether there can be multiple equilibria. In order to do that, we examine the interaction between the number of vehicles (x_i) and the number of stations (M_i) for a given technology. Equation (6) expresses the consumer's demand for vehicles x_i as a function of M_i (and x_{-i}), while equation (9) determines the number of stations M_i as a function of x_i. An equilibrium requires that these two equations are simultaneously fulfilled.

Equation (6) can be simplified to:

$$x_i(M_i, x_{-i}) = g(M_i, x_{-i}) = A_i(x_{-i}) + B_i M_i^{\zeta_i} \tag{10}$$

where

$A_i(x_{-i}) = \frac{1}{b_i}(a_i - \phi x_{-i} - p_i(1 - u_i))$ (A_i can be either positive or negative).

$B_i = \frac{1}{b_i}\left(\kappa_i^{\frac{1}{1-\beta_i}} (\omega_i(1 - s_i))^{\frac{-\beta_i}{1-\beta_i}} \beta_i^{\frac{\beta_i}{1-\beta_i}} (1 - \beta_i)\right) > 0$

[4] The utility function implies that the elasticity of substitution for charging/filling between the differentiated stations is $\frac{-1}{1-\rho_i}$, implying a markup of $\frac{1}{\rho_i}$. This only holds when M_i is large. When e.g. $M_i = 1$, the markup is higher and equal to $\frac{1}{\beta_i}$, but then it is no longer monopolistic competition but monopoly.

[5] It is possible to insert equation (9) into the vehicle demand equation (6), and then derive an expression for the number of vehicles of type i as an implicit function of only exogenous parameters plus the number of vehicles of the other type, $-i$.

$\zeta_i = \frac{\beta_i(1-\rho_i)}{\rho_i(1-\beta_i)} > 0$

Equation (9) can be rewritten so that the number of stations (M_i) is an implicit function of the number of vehicles (x_i):

$$x_i(M_i) = h(M_i) = C_i M_i^{\gamma_i} \tag{11}$$

where

$C_i = \frac{f_i(1-\sigma_i)(1-s_i)^{\frac{1}{1-\beta_i}} \psi_i^{\frac{\beta_i}{1-\beta_i}}}{(\kappa_i\beta_i)^{\frac{1}{1-\beta_i}} \rho_i^{\frac{\beta_i}{1-\beta_i}} (1-\rho_i)} > 0$

$\gamma_i = \frac{\rho_i-\beta_i}{\rho_i(1-\beta_i)} > 0$

Both ζ_i and γ_i are between 0 and 1, which means that both $g(M_i, x_{-i})$ and $h(M_i)$ are increasing and concave in M_i. Because of the functional forms, equations (6) and (9) can be jointly satisfied for either 0, 1 or 2 values of M_i. Which of the two functions that has the highest value as M_i goes to infinity, depends on the exponents ζ_i and γ_i. Hence, an important question is which of these is largest. Another important question is whether $A_i(x_{-i})$ is positive or negative, and we will return to that question below.

If $\zeta_i > \gamma_i$, then $g(M_i, x_{-i})$ exceeds $h(M_i)$ for all $M_i > M_i^*$, where M^* is the equilibrium with the highest level of M (if there are no equilibria, $M^* = 0$). In this case, the equilibrium with $M_i = M_i^*$ is unstable. This means that if we are in a situation with M_i and x_i larger than (M_i^*, x_i^*), then M_i and x_i will go to infinity.[6] This seems very unlikely and we thus assume $\zeta_i \leq \gamma_i$, which implies $\beta_i \leq \frac{\rho_i}{(2-\rho_i)}$, that is, β_i cannot be too close to ρ_i.

If $\zeta_i = \gamma_i$, then M_i has the same exponent in equation (10) and (11), and the curves can cross zero or only one time. It is not very likely, and since an equilibrium is unstable if $A_i < 0$, we also rule out this case.

Hence, from here we assume $\zeta_i < \gamma_i$, that is $\beta_i < \frac{\rho_i}{2-\rho_i}$, in which case the number of equilibria depends especially on $A_i(x_{-i})$. Under what conditions are there 0, 1 or 2 equilibria?

2.2.1 Three different cases

We have one (and only one) equilibrium if $A_i(x_{-i}) = \frac{1}{b_i}(a_i - \phi x_{-i} - p_i(1-u_i)) > 0$, and we refer to this as case I. The equilibrium in case I is stable (cf. the discussion above). This case can be seen in the first graph in Figure 1. If $A_i(x_{-i}) < 0$, we have either two or zero equilibria, and we refer to these cases as case II and case III, respectively.[7] These are illustrated in the second and third graphs in Figure 1.

We see that the likelihood of $A_i(x_{-i}) > 0$ increases:

- the lower the price of the vehicle, including a potential subsidy of the vehicle ($p_i(1-u_i)$),
- the higher the utility of the first vehicle (a_i), irrespective of possibility of charging/filling at stations, and
- the fewer vehicles of the other technology (x_{-i}) and the lower the substitutability between the two technologies (ϕ).

These three items in combination determine whether or not $A_i(x_{-i}) > 0$, in which case the consumer has positive net utility from the first vehicle even without any stations.

[6]Assume e.g. that M_i is optimally chosen for a given x_i, so that (9) is fulfilled, but x_i is not, so that (6) is not fulfilled. Then it is optimal for the consumer to increase x_i since $g(M_i) > h(M_i)$, so that (6) is fulfilled. But then (9) is no longer fulfilled, and hence M_i must increase to fulfill (9) (again since $g(M_i) > h(M_i)$) etc etc. On the other hand, if $g(M_i) < h(M_i)$ when M_i goes to infinity, which is the case if $\zeta_i < \gamma_i$, the equilibrium is stable.

[7]If $A = 0$, there is either 0 or 1 strictly positive equilibrium, and thus we consider the former case as Case III and the latter case as Case I.

A positive $A_i(x_{-i})$ seems more likely for electric than for hydrogen vehicles. Electric vehicles can to some degree can be charged at home, while hydrogen vehicles cannot be filled without a hydrogen station. Therefore, the utility of the first electric vehicle (a_i) when there are no stations is probably higher for electric vehicles than for hydrogen vehicles. In addition, as electric vehicles have gotten a head on hydrogen vehicles in many countries, x_{-i} is probably highest for hydrogen vehicles (but that depends on the specific region investigated).

Whether we are in case II or III when $A_i < 0$, depends on whether $h(M_i)$ is always above $g(M_i, x_{-i})$ (case III), or whether $g(M_i, x_{-i})$ is above $h(M_i)$ for some interval (M_i^{*U}, M_i^{*S}), where M_i^{*U} and M_i^{*S} are respectively an unstable and a stable equilibrium.[8] This further depends on the size of both $A_i(x_{-i})$, B_i and C_i, as well as the two exponents. The higher is $A_i(x_{-i})$, B_i and ζ_i, and the lower is C_i and γ_i, the more likely we are in case II with two equilibria. Moreover, the location of the equilibrium in case I and the stable equilibrium in case II also depends in the same way on the size of $A_i(x_{-i})$, B_i, C_i, ζ_i and γ_i.

From examination of how the different parameters enter in (6) and (9), it is straightforward to show that both the likelihood of an equilibrium and the size of x_i and M_i in the stable equilibrium increases:

- the lower the purchase price of the vehicle, including a potential subsidy ($p_i(1 - u_i)$),
- the higher the utility of the first vehicle (a_i), irrespective of possibility of charging/filling at stations,
- the fewer vehicles of the other technology (x_{-i}) and the lower the substitutability between the two technologies (ϕ),
- the smaller the fixed costs of the stations (f_i),
- the smaller the marginal cost of charging/filling (ψ_i), and
- the higher the utility of charging/filling (κ_i).

The findings above also hold when we take into account indirect effects via x_{-i}, since higher x_i leads to lower x_{-i}, which increases x_i further (see below).

It is straightforward to show that the size of x_i and M_i in the unstable equilibrium goes in the opposite direction as in the stable equilibrium.[9]

Case II with one stable and one unstable equilibrium is of special interest. In this case, one cannot expect the market to move towards the stable equilibrium by itself if x_i and M_i start at low levels, i.e., lower than in the unstable equilibrium. Then the (representative) consumer may think there are too few stations, and scale down its number of vehicles, while the station owners may face negative profits and prefer to contract. Hence, we could see a negative spiral going towards zero vehicles and zero stations.[10]

On the other hand, if we initially are beyond the unstable equilibrium, $(M_i, x_i) > (M_i^{*U}, x_i^{*U})$, we may see a positive spiral moving towards the stable equilibrium.

Before turning to the effect of policy, it is also worth noticing the interactions between the two technologies. As shown above, the higher is x_{-i}, the more likely it is that no equilibrium exists (case III). Moreover, if we are in case II, the size of M_i and x_i in the unstable equilibrium increases with x_{-i}, making it more difficult to reach the stable equilibrium. Thus, if one technology has gotten a head start, it can be more and more difficult for the other technology to enter the market.

It also follows that for some model parameters, we may have a situation where the three following stable equilibria are all feasible: i) There are only electric vehicles, ii) there are only hydrogen vehicles, and iii)

[8] Cf. the explanation above about stable vs. unstable equilibria. Remember also that $h(M_i) > g(M_i, x_{-i})$ when M_i goes to infinity.

[9] For instance, assume that C_i increases due to an increase in f_i, so that the $h_i(M_i)$ curve shifts up. Then the intersection points in Figure 1 (case II) move towards each other.

[10] See Greaker and Heggedal (2010) and Zhou and Li (2018) for a similar discussion of stable and unstable equilibria.

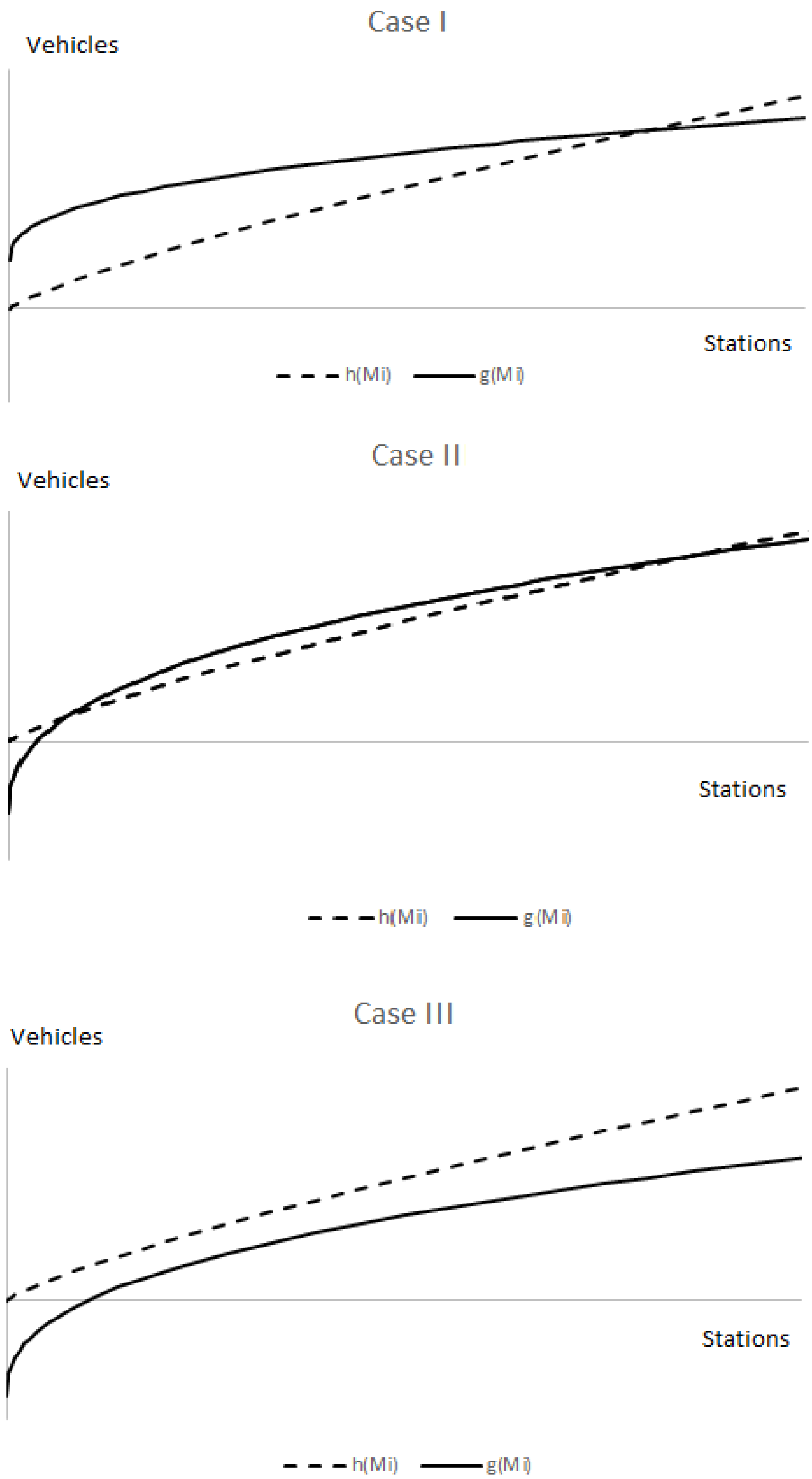

Figure 1: The three cases illustrated.

there are both electric and hydrogen vehicles. Which equilibrium that evolves will be path dependent, but this is beyond the scope of our theoretical analysis. We will turn to this question in the numerical analysis.

2.3 Effects of policy

Because of the network effects and monopolistic pricing of charging/filling, policy makers may want to implement subsidies to building of stations (σ_i), and/or to charging/filling (s_i), and/or to vehicles (u_i). In the next section we examine optimal policies, but first we consider the effects of subsidies on the likelihood of a market equilibrium and the size of x_i and M_i in a stable equilibrium.

First, notice that subsidies to purchase of vehicles can affect whether $A_i > 0$ and hence whether or not we are in case I. The subsidies to stations and charging/filling on the other hand do not affect whether or not we are in case I with $A_i > 0$. If $A_i > 0$, we will have a market equilibrium no matter what the subsidies to stations and charging/filling are. On the other hand, if $A_i < 0$, the subsidies to stations and charging/filling may affect whether there will be 2 or 0 equilibria (case II or III). The higher the subsidies to stations and charging/filling, the more likely we are in case II.[11]

Both in case I and II, the subsidies affect where the equilibrium is, i.e., the size of x_i and M_i. A higher s_i decreases $h_i(M_i)$ and increases $g_i(M_i, x_{-i})$, whereas a higher σ_i decreases $h_i(M_i)$. Thus, in both cases I and II, the higher is s_i and the higher is σ_i, the higher is (M_i^{*S}, x_i^{*S}) and the lower is (M_i^{*U}, x_i^{*U}). Hence, the subsidies may also make it easier to move beyond the unstable equilibrium, i.e., helping the market to move towards the stable equilibrium.

Before turning to the welfare effects, we summarize our results so far in the following proposition:

Proposition 1 *Consider a market with two potential transport technologies as described above. Then we have that:*

- *If the utility of the first vehicle (a_i) is sufficiently high, i.e., $a_i > p_i(1-u_i) + \phi x_{-i}$, there is one unique stable equilibrium.*
- *If $a_i < p_i(1-u_i) + \phi x_{-i}$, there is either zero or two equilibria. In the latter case, the equilibrium with highest values of x_i and M_i is stable, while the other is unstable.*
- *Both the probability of the existence of an equilibrium and the number of vehicles (x_i) and stations (M_i) as well as total charging/filling (q_iM_i) in a stable equilibrium increases i) the higher the utility of the first vehicle (a_i), ii) the lower the substitutability between the two vehicle technologies (ϕ), iii) the lower the number of the vehicles of the other technology (x_{-i}), iv) the lower the annual price of the vehicle (p_i), v) the lower the fixed costs of the stations (f_i), vi) the lower the marginal cost of charging/filling (ψ_i), vii) the higher utility of charging/filling (κ_i), and viii) the higher subsidies for stations, charging/filling and vehicles (s_i, σ_i and u_i).*
- *The sizes of x_i, M_i and q_iM_i in an unstable equilibrium goes in the opposite direction as in a stable equilibrium.*

3 Welfare effects

In the previous section, we derived conditions that must hold in equilibrium, examined under what conditions an equilibrium exists, and whether there can be multiple equilibria. In this section we search for the social optimal solution, and compare this with the market solution without and with policy. Initially, we assume

[11] σ_i and s_i both enter negatively in C_i, and s_i also enters positively in B_i.

that there exists a stable market equilibrium where both technologies are in use, focusing on policies that are locally optimal. Next, we discuss whether the market will provide the optimal number of technologies.

3.1 Welfare maximization problem: First-best solution

The social planner maximizes domestic welfare. The social welfare function is assumed to be utilitarian, meaning that it is the unweighted sum of consumer surplus, producer surplus and net government revenues, or equivalently the gross utility of the representative consumer minus the total vehicle-related costs:

$$W = I + \sum_{i=1}^{2} a_i x_i - 1/2(b_1 x_1^2 + 2\phi x_1 x_2 + b_2 x_2^2) - \sum_{i=1}^{2} p_i x_i + \sum_{i=1}^{2} \left(x_i \kappa_i M_i^{\frac{\beta_i}{\rho_i}} q_i^{\beta_i} \right) - \sum_{i=1}^{2} (x_i M_i \psi_i q_i + f_i M_i) \quad (12)$$

where the second and third terms are the gross utility of vehicles, the fourth term includes the costs of buying these vehicles (e.g. from abroad), the fifth term is the utility from charging/filling, while the sixth and the seventh terms include the total costs of charging/filling.

After deriving the first order conditions, we get the following expressions for the optimal level of x_i, q_i and M_i:

$$x_i(M_i, x_{-i}, q_i) = \frac{1}{b_i} \left(a_i - \phi x_{-i} + \kappa_i M_i^{\frac{\beta_i}{\rho_i}} q_i^{\beta_i} - p_i(1 - u_i) - M_i \psi_i q_i \right) \quad (13)$$

$$q_i(M_i) = M_i^{-\frac{\rho_i - \beta_i}{\rho_i(1-\beta_i)}} \left(\frac{\kappa_i \beta_i}{\psi_i} \right)^{\frac{1}{1-\beta_i}} \quad (14)$$

$$M_i(x_i, q_i) = \left(\left(\psi_i q_i^{1-\beta_i} + \frac{f_i}{x_i q_i^{\beta_i}} \right) \frac{\rho_i}{\kappa_i \beta_i} \right)^{-\frac{\rho_i}{\rho_i - \beta_i}} \quad (15)$$

By inserting (14) into respectively (13) and (15), it is straightforward to derive the following expressions for the optimal levels of x_i and M_i:

$$x_i(M_i, x_{-i}) = \frac{1}{b_i} \left(a_i - \phi x_{-i} - p_i(1 - u_i) + \kappa_i^{\frac{1}{1-\beta_i}} M_i^{\frac{\beta_i(1-\rho_i)}{\rho_i(1-\beta_i)}} \psi_i^{\frac{-\beta_i}{1-\beta_i}} \beta_i^{\frac{\beta_i}{1-\beta_i}} (1 - \beta_i) \right) \quad (16)$$

$$M_i(x_i) = \left(\frac{x_i}{f_i} \right)^{\frac{\rho_i(1-\beta_i)}{\rho_i - \beta_i}} \psi_i^{\frac{-\rho_i \beta_i}{\rho_i - \beta_i}} (\kappa_i \beta_i)^{\frac{\rho_i}{\rho_i - \beta_i}} (1 - \rho_i)^{\frac{\rho_i(1-\beta_i)}{\rho_i - \beta_i}} \rho_i^{\frac{-\rho_i(1-\beta_i)}{\rho_i - \beta_i}} \quad (17)$$

Next, we want to compare the first best solution with the market outcome, starting with the case without any subsidies which we term business-as-usual (BAU).

3.2 Market solution without policy (BAU)

The market solution without any subsidies (BAU) means that we have $s_i = 0$, $\sigma_i = 0$ and $u_i = 0$. Demand for vehicles is then (equation (6) with $s_i = u_i = 0$ and replacing ω_i with ψ_i/ρ_i):

$$x_i(M_i, x_{-i}) = \frac{1}{b_i} \left(a_i - \phi x_{-i} - p_i + \kappa_i^{\frac{1}{1-\beta_i}} M_i^{\frac{\beta_i(1-\rho_i)}{\rho_i(1-\beta_i)}} \left(\frac{\psi_i}{\rho_i}\right)^{\frac{-\beta_i}{1-\beta_i}} \beta_i^{\frac{\beta_i}{1-\beta_i}} (1 - \beta_i) \right) \quad (18)$$

Demand for charging/filling becomes (equation (5) with $s_i = 0$):

$$q_i(M_i) = M_i^{-\frac{\rho_i - \beta_i}{\rho_i(1-\beta_i)}} \left(\frac{\kappa_i \beta_i \rho_i}{\psi_i}\right)^{\frac{1}{1-\beta_i}} \tag{19}$$

The number of stations in the BAU solution is (equation (9) with $\sigma_i = 0$ and $s_i = 0$):

$$M_i(x_i) = \left(\frac{x_i}{f_i}\right)^{\frac{\rho_i(1-\beta_i)}{\rho_i - \beta_i}} \psi_i^{\frac{-\rho_i \beta_i}{\rho_i - \beta_i}} (\kappa_i \beta_i)^{\frac{\rho_i}{\rho_i - \beta_i}} (1-\rho_i)^{\frac{\rho_i(1-\beta_i)}{\rho_i - \beta_i}} \rho_i^{\frac{\rho_i \beta_i}{\rho_i - \beta_i}} \tag{20}$$

Comparing first (20) with (17), we see that they are identical except for the last factor, which is highest in (17) (since $\rho_i < 1$). Hence, the BAU solution will lead to fewer stations than the optimal solution. The lower is ρ_i, i.e., the less perfect substitutes the different stations are, the bigger is the difference between the optimal and the BAU solution.

Next, comparing (19) with (14), we find that they are also almost identical, except for two things: The level of M_i differs, as we have just explained, and there is an additional ρ_i inside the parenthesis of (19). The latter implies too little charging/filling in the BAU solution compared to the optimal solution, and is due to the monopoly pricing. The lower level of M_i implies higher level of q_i, i.e., charging/filling at each station, so we cannot say whether q_i is higher or lower in the BAU solution. However, the total amount of charging/filling per vehicle ($q_i M_i$) is unambiguously lower in the BAU solution, due to both lower level of M_i and the monopoly pricing.

Last but not least, comparing (18) with (16) shows that the last term inside the parenthesis is lower in the BAU solution, both because of the parameter ρ_i and since the level of M_i is lower. Thus, if the two vehicle types are symmetric, the number of vehicles is too low in the BAU solution.[12]

To summarize:

- $M_i^{BAU} < M_i^*$
- $q_i^{BAU} M_i^{BAU} < q_i^* M_i^*$
- $x_i^{BAU} < x_i^*$ if the two technologies are symmetric

3.3 Optimal policy

Can the first best policy be implemented in the market, through an appropriate set of subsidies? To examine this, we compare equations (14), (16) and (17) with respectively equations (5), (6) and (9).

First, comparing (14) with (5), we see that the optimal level of charging/filling can be realized by setting the subsidy s_i equal to $1 - \rho_i$, cf. equation (7), i.e., correcting for the monopoly markup.

Next, we notice that by inserting $s_i = 1 - \rho_i$ into (6) and (9), using that $\omega_i \rho_i = \psi_i$, these equations become identical to (16) and (17) if and only if $\sigma_i = 0$. Hence, the optimal solution can be implemented simply by correcting for the monopoly pricing in the charging and filling stations - then there is no need for a subsidy to building the stations. There is also no need to subsidize purchase of vehicles.

From the discussion in subsection 2.2 we know that the higher s_i (and σ_i and u_i), the higher the stable equilibrium (M_i^*, x_i^*). This confirms what we found at the end of the previous subsection, i.e., the optimal solution will have higher levels of vehicles and stations than the BAU solution.[13]

[12] With asymmetric vehicle types, we cannot rule out the case that the number of vehicle is highest in the BAU solution for one of the vehicle types.

[13] Higher levels of vehicles in the optimal solution than in the BAU solution can only be shown if the technologies are symmetric. Remember that environmental externalities are not part of the model.

We summarize this finding in the following proposition:

Proposition 2 *Consider a market with two potential transport technologies as described above, and assume that the market develops towards a stable equilibrium with the optimal number of technologies. Then the optimal solution can be realized in the market through subsidizing charging/filling at the rate* $s_i = 1 - \rho_i$*. Then there is no need to supplement with subsidies to investments in stations. The number of vehicles, stations and total charging/filling is higher in the first best solution than in the BAU solution.*

If we are in case I with $A_i(x_{-i}) > 0$, there is only one equilibrium, which is stable. In this case, the market is likely to move towards this equilibrium, and the policy described in Proposition 2 should be sufficient. Note, however, that $A_i(x_{-i})$ is decreasing with x_{-i}, so that we may move from case I to case II to case III for technology i as x_{-i} increases.

If we are not in case I, things are more complicated. First, we noticed in subsection 2.2 that the likelihood of the existence of an equilibrium increases with the subsidies (if $A_i(x_{-i}) < 0$), and that the size of an unstable equilibrium decreases with the subsidies. Thus, it may be the case that no market equilibrium exists without any policy, while it exists with the first best policy. Moreover, if a stable market equilibrium exists even without policies, it will be less difficult to reach this equilibrium with first best policy since the unstable equilibrium is then characterized by lower levels of vehicles and stations.

Hence, even if we do not observe any market developing for one of the technologies, it might be optimal to use this technology, too. This can also be the case even if the first-best policies described in Proposition 2 are in place. Thus, the market may need additional policies initially to find the stable and optimal equilibrium. It may be difficult for policy makers, however, to know whether or not it is optimal with an additional technology.

It is difficult to formulate analytical conditions for whether it is optimal with one or two technologies. For this purpose, we will have to rely on numerical simulations, cf. section 4. But first we will briefly consider second-best policies, that is, when the first-best policies are not available.

3.4 Second-best policy

It may be politically difficult to subsidize the markup in charging/filling, e.g., because it may be expensive for the government, and subsidies to investments in stations and vehicles are more common. What is the optimal level of σ_i and/or u_i in this case (i.e., if $s_i = 0$)?

As noted in subsection 2.3, a higher s_i decreases $h_i(M_i)$ and increases $g_i(M_i, x_{-i})$, whereas a higher σ_i only decreases $h_i(M_i)$. Thus, as σ_i increases, we move to the right along the $g_i(M_i, x_{-i})$ curve in Figure 1, while the first-best solution (with $s_i > 0$) lies above the $g_i(M_i, x_{-i})$ curve. Hence, a second-best policy with only subsidies to stations will likely lead to more stations per vehicle than in the fist-best solution, and there will be a trade-off between too many stations or too few vehicles. If also subsidies to vehicles are used, it is possible to obtain the optimal number of both M_i and x_i.[14] However, the level of charging/filling will be suboptimal as the consumer will have to pay the full price. It is difficult to derive an expression for the second-best investment subsidy, and also to know whether it should be differentiated across technologies. Instead we come back to this in the numerical analysis.

[14] σ_i can be adjusted so that $h(M_i)$ passes through the optimal levels of x_i and M_i, and u_i can be adjusted so that $g(M_i, x_{-i})$ also passes through these levels, cf. equations (10) and (11).

4 Numerical analysis

4.1 Calibration

We calibrate the model based on data and future projections for the Norwegian vehicle market. Norway has a very large share of electric vehicles compared to most other countries, with more than 40% of new sales of cars in 2019. The calibration of a future equilibrium is obviously uncertain, as this is currently an emerging market. The uncertainty is both related to how the technologies and the market structure will develop the next years, as well as the consumers' utility from owning and using (i.e., charging/filling) the two types of vehicles (cf. the sensitivity analysis in section 4.7). A reasonable calibration is anyway useful in order to gain more insight into how different cost and utility parameters may affect the market outcome as well as the importance of policies. In particular, our goal is to get insight into the *factors* that determine whether we should have one or two technologies in a fully decarbonized road transport sector.

It seems most natural to consider the calibrated equilibrium as the first best solution, as the transition towards a decarbonized transport market in Norway is highly driven by government policies.[15] Moreover, we first assume that there are only electric vehicles in this first-best equilibrium, as electric vehicles are much more prevalent today than hydrogen vehicles. Subsequently, we introduce hydrogen vehicles into the numerical model. Details about assumptions, sources and numbers are found in Appendix A.

In the calibrated first-best equilibrium there are (by construction, see Appendix A) 3.6 million electric vehicles ($x_1 = 3.585$ mill), almost 5,000 charging stations ($M_1 = 4,975$), and charging per vehicle per station is $q_1 = 0.014$. Moreover, we are in Case I, i.e., with only one (stable) equilibrium, as $a_1 = p_1$ and there are no hydrogen vehicles (cf. the discussion in section 2.2.1 and footnote 7).

Calibration of the hydrogen network and vehicles is even more uncertain, and to some degree we apply the same parameters as for electric vehicles. However, as hydrogen vehicles are more dependent on the network than electric vehicles, we assume $a_2 = 0.5p_2$ and $\kappa_2 > \kappa_1$ (cf. equation (1)). We assume that the price of hydrogen and electric vehicles are the same in our future equilibrium. To make the two networks comparable, we require in the calibration that the level of x_2 in the first-best equilibrium with only hydrogen vehicles is the same as that of x_1 (with only electric vehicles). For details, see Appendix A.

In the following subsection we examine the market with only electric vehicles, comparing the optimal and the BAU solution. Then we introduce hydrogen vehicles, and consider first a hypothetical market with only hydrogen vehicles. Next, we consider the interactions between the two technologies, and in particular investigate the market outcome when the two technologies are either close substitutes (case A) or distant substitutes (case B), see the Appendix A for specification. An overview of the results can be found in Appendix C.[16]

4.2 The road transport market with only one technology

4.2.1 Electric vehicles only

The first-best outcome with only electric vehicles is illustrated in Figure 2. We see that the $h(M_i)$ curve is almost linear, meaning that the number of stations responds almost proportionally to the number of vehicles. The $g(M_i)$ curve, however, is highly concave, with the number of vehicles initially rising rapidly with the number of stations, but then almost leveling off when there are a few hundred stations. The first-best

[15] For instance, the Norwegian government has decided that from 2025 sales of new cars will only be non-fossil vehicles (The Norwegian Parliament (Stortinget), 2017)

[16] The model is solved using GAMS. The model code and data to replicate simulation results are readily available upon request.

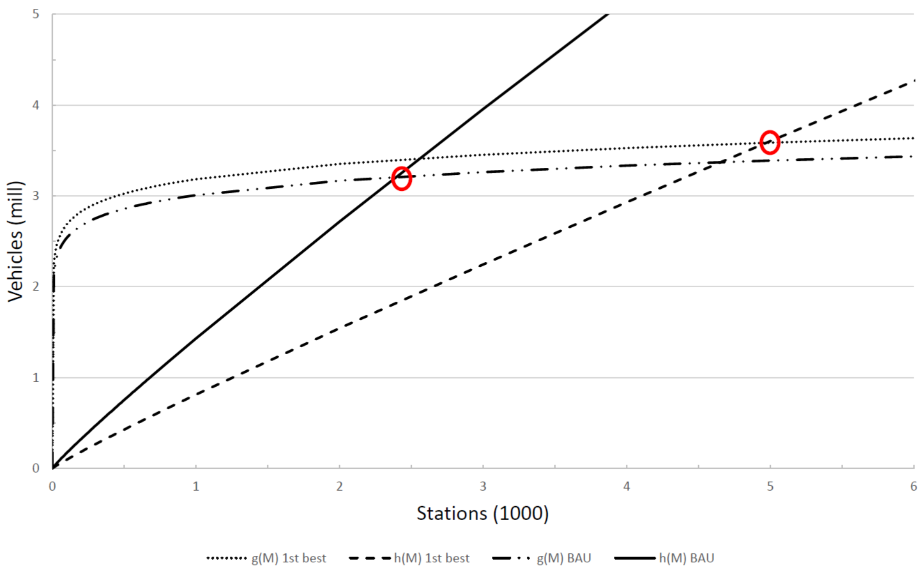

Figure 2: First-best and BAU equilibrium with only electric vehicles in the market.

equilibrium is found where these two curves intersect (cf. the numbers mentioned in information about the calibration in the Appendix A).

We then compare this first-best (calibrated) equilibrium with the corresponding BAU outcome, that is, when there are no policies. Also in the BAU scenario we are in Case I (one equilibrium). Remember that according to Proposition 2, the first-best solution can be realized in the market via a subsidy to charging equal to $s = 1 - \rho$, so going from first-best to BAU simply means to remove this subsidy.

Not surprisingly, in the BAU solution there is less charging per vehicle, as charging is no longer subsidized. Total charging per vehicle ($q_1 M_1$) drops by 47%. It is mainly the number of stations that is affected. It drops substantially when charging becomes more expensive, from $4,975$ to $2,394$, see Figure 2. Because of this, charging per station per vehicle (q_1) increases slightly, from 0.014 to 0.016. Further, more expensive charging and fewer stations reduce the demand for electric vehicles, but only by 10%. Total welfare in the road transport market (i.e., all terms except the first in equation (12)) declines by 6%, from 37.3 billion NOK per year to 35.1 billion.

4.2.2 Hydrogen vehicles only

Before considering the interactions with the hydrogen network and vehicles, we briefly look at a hypothetical market with only hydrogen vehicles. In the first-best equilibrium, the number of vehicles is (by construction) $x_2 = 3.585$ million. There are somewhat fewer stations, but more filling per station, than in the case with electric vehicles only: $M_2 = 4,054$ and $q_2 = 0.019$. As $a_2 < p_2$ (and $x_1 = 0$) we are in Case II with two equilibria, see more details in Appendix B, including Figure 8 illustrating this situation. The demand for hydrogen vehicles continues to be somewhat responsive to the number of stations also when there are more than a few hundred stations (as opposed to electric vehicles). The unstable equilibrium is very small, meaning very low levels of hydrogen vehicles (x_2) and hydrogen stations (M_2) need to be passed in order to reach the first-best equilibrium (with subsidies to filling in place).

In the first-best solution, total welfare when there is only hydrogen vehicles is 3.4 billion NOK lower than in the case with only electric vehicles (in BAU, the difference is 4.3 billion NOK). This is probably due to the higher costs of hydrogen stations and hydrogen filling, and the lower utility of the first hydrogen vehicle

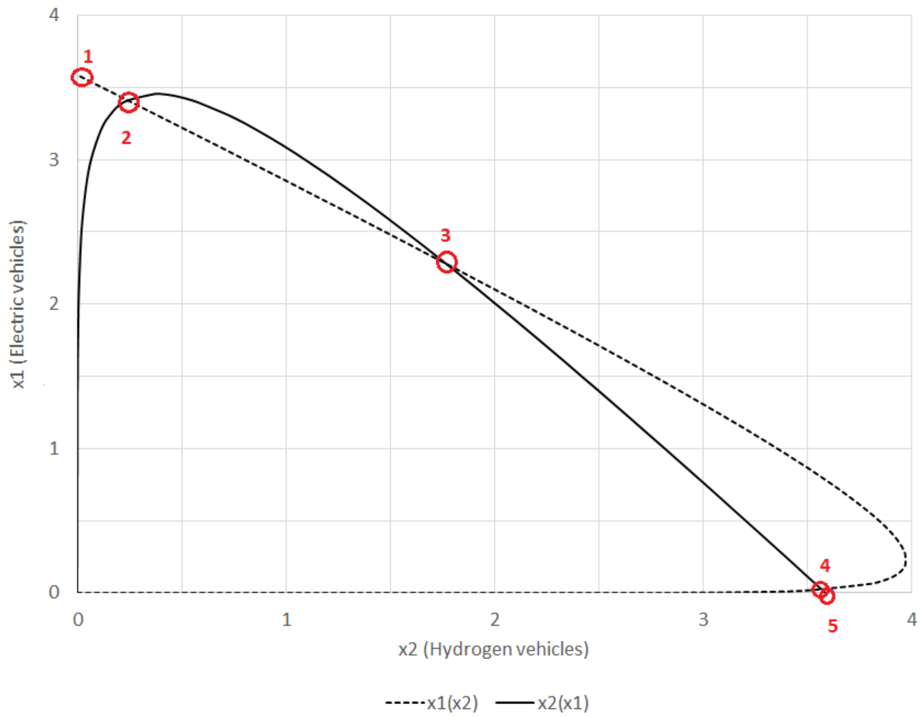

Figure 3: Graph showing how the number of hydrogen (electric) vehicles depends on the number of electric (hydrogen) vehicles. Five equilibria are shown, where three are stable (1, 3 and 5) and two unstable (2 and 4)

(compared to electric vehicle). The prices of hydrogen and vehicles are assumed to be the same.

4.3 Effects of the other technology on the number of vehicles

In this subsection we will investigate how the hydrogen network and vehicles depends on the number of electric vehicles, where we treat the latter as exogenous, and vica versa. In the next subsection, subsection 4.4, both technologies are treated as endogenous. As discussed in section 2.2.1, the higher the number of vehicles of the other technology (x_{-i}), the more likely is it that no equilibrium exists for technology i. However, this also depends on how close substitutes they are, represented by the parameter ϕ. The higher is ϕ, the lower is the likelihood of equilibria for technology i (for a given number of (x_{-i})). Here we assume that the technologies are close substitutes (case A).

Figure 3 illustrates how the number of electric vehicles (vertical axis) affects the number of hydrogen vehicles (horizontal axis), and vice versa. The figure is inspired by Figure 2 in Katz and Shapiro (1985). The solid curve shows the reaction function of hydrogen vehicles with the number of electric vehicles as exogenous, while the dotted curve shows the reaction function of electric vehicles with the number of hydrogen vehicles as exogenous. There are five equilibria, where three are stable (denoted 1,3 and 5). Equilibrium no. 3 is the only stable equilibrium with two technologies. This equilibrium is also illustrated in figure 4. There are also two unstable equilibria (2 and 4). If the number of hydrogen vehicles are lower than in equilibrium 2, hydrogen vehicles will not reach critical mass and move towards zero. If the number of hydrogen vehicles are higher than in equilibrium 2, it will instead move towards equilibrium 3. For electric vehicles, it is the same situation with equilibrium 4. We see from Figure 3 that electric vehicles need a lower number of vehicles before the unstable equilibrium is passed compared to hydrogen vehicles.

This shows that when the two technologies are close substitutes, the first-best solution for the hydrogen network and vehicles depends crucially on the number of electric vehicles. Assume for instance that first-best subsidies to charging have been put in place, and that electric vehicles have been established in the market with a large number of vehicles. Then the hydrogen network will not be established even if first-best subsidies to filling is also implemented. However, this conclusion depends crucially on the timing, which we do not model. In the next subsection we endogenize the number of vehicles of both technologies, and then we find that it is optimal with two technologies in the market. However, as showed here, it might not happen as electric vehicles have gotten a head of hydrogen vehicles.

4.4 Interactions between technologies – first-best

We now consider the interactions between the two technologies when both are endogenous, and start with the first-best solution (in the next subsection (subsection 4.5) we compare the first-best and the BAU solution). In particular, we are interested in comparing the outcome with two technologies available with a situation with only one technology. Again we distinguish between close and distant substitutes. The results for distant substitutes can be found in the Appendix B.

When the two technologies are *close* substitutes, the number of electric vehicles is reduced by 36% in the first-best solution compared to when electric vehicles are alone in the market, see Figure 4. Hydrogen vehicles are reduced by 51% compared to when they are alone in the market. There are more vehicles in total with two technologies, than with only one technology. Even if the technologies are close substitutes, they are still somewhat differentiated. The market share of electric vehicles in this case is 56%. The number of charging and filling stations decrease by respectively 39% and 53% when going from one to two technologies. Charging/filling per vehicle does not change much, while charging/filling per station per vehicle increases.

We see from the figure that electric vehicles move from being in case I to being in case II when there are two technologies in the market. This means that if the number of hydrogen vehicles were to increase first, the electric vehicles might need critical mass in order to overcome the unstable equilibrium, or else electric vehicles may not get a foothold in the market. Hydrogen vehicles stay in case II when there are two technologies in the market.

The annual welfare in the road transport sector increases by 704 million NOK (+2%) when there are two technologies compared to the case with only electric vehicles, and by 4.1 billion NOK (+12%) compared to the case with only hydrogen vehicles. Thus, the importance of having two instead of one vehicle technology is quite moderate when the technologies are close substitutes.

4.4.1 When is only one technology optimal?

Figure 5 shows the first-best welfare with either one or two technologies for different values of ϕ. When $\phi = b = 6.8$, the technologies are perfect substitutes. The figure confirms what we noticed above, that is, the welfare gains from using both technologies are much higher when the two technologies are distant substitutes. The figure further shows that when ϕ exceeds 4.7, using only electric vehicles is welfare-superior compared to using both technologies. When ϕ is between 4.7 and 5.1, implementing the first-best policy proposed in Proposition 2 can in fact lead to a market equilibrium with both technologies in use, even if welfare is higher when only using electric vehicles. When ϕ is higher than 5.1, only one technology can sustain in the market with first-best policy.

4.5 Interactions between technologies – comparing BAU and first-best

We now compare the first-best solution described above with the corresponding BAU outcome, again distinguishing between close and distant substitutes. When charging/filling is no longer subsidized in BAU and

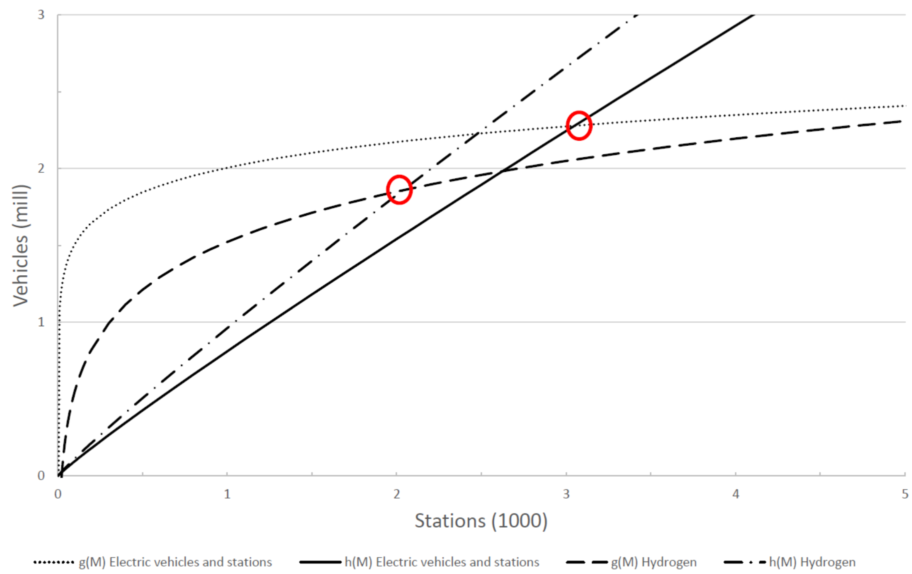

Figure 4: Graph showing the first-best equilibrium for the electric vehicles and station market and the hydrogen market when the technologies are close substitutes.

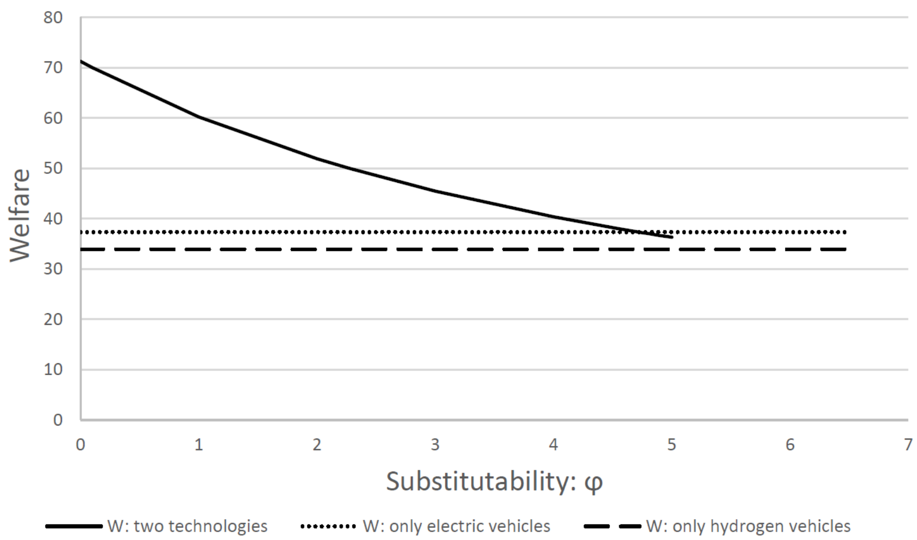

Figure 5: Graph showing how the welfare of having two technologies reduces the closer substitutes the two technologies become.

the technologies are close substitutes, there is no feasible market equilibrium with both technologies in use. This means that the two reaction curves in Figure 3 do not cross. We cannot know for certain whether the market will choose electric or hydrogen vehicles. However, when comparing with first-best we will assume that the market chooses the equilibrium with the highest welfare, which is the one with electric vehicles.

The total number of vehicles are reduced by 21% in BAU with one technology compared to the first-best outcome with two technologies. The number of electric vehicles increases by 41% in the BAU since this technology is now alone in the market. Charging per vehicle per station decreases by 30% when charging is no longer subsidized in the BAU outcome. Therefore, even if the number of electric vehicles increases, the number of charging stations decreases by 21%. The reduction in annual welfare in the road transport market in BAU compared to first-best is 8% (2.9 billion NOK). In contrast, when the technologies are distant substitutes, the market shares only change slightly in BAU compared to the first-best outcome. The results for the distant substitutes can be found in the Appendix B.

4.6 Second-best solutions

For various reasons, the first-best policy may not be feasible or desired by the government. First, subsidizing investments in stations and purchase of vehicles may be easier to implement and administer than subsidizing charging/filling. Second, public expenditures may be higher when subsidizing charging/filling, in which case it may be more desirable to subsidize stations and/or vehicles. This is indicated by subsidies to stations and vehicles being more widespread than subsidies to charging/filling in the world today (IEA, 2019).

In this subsection, we investigate two kinds of second-best policies. The first is to give an investment subsidy to the stations, and we refer to this as second-best I. The second is a combination of a subsidy to stations and to vehicles, and refer to this as second-best II. Obviously, welfare in second-best II will be at least as high as in second-best I. We focus on case A here (close substitutes), and present results for case B (distant substitutes) in the Appendix B.

4.6.1 Second-best I (subsidy to stations)

When the two technologies are close substitutes, subsidizing stations instead of charging/filling leads to almost the same number of fast charging stations as in the first-best solution (13 more in the first-best than in the second-best I solution), and more (668) than in the BAU outcome. The same applies for hydrogen stations compared to the first-best outcome (171 fewer than in first-best), but far more than in BAU (1,741) – remember that in BAU the number of hydrogen stations is zero. However, charging per vehicle is reduced by 43% compared to the first-best outcome, and is only somewhat higher than in the BAU outcome (4%). For hydrogen it is different since there are no hydrogen vehicles and stations in the BAU outcome. The filling per vehicle is reduced by 37% compared to the first-best solution. The second-best subsidy rates to fast charging and filling stations are respectively $\sigma_1 = 0.42$ and $\sigma_2 = 0.47$.

The number of electric vehicles is slightly higher in the second-best I solution (2.342 million) than in the first-best outcome (2.278 million), as the number of hydrogen vehicles is lower (see below), but it is lower than in the BAU outcome (remember that the number of electric vehicles is higher in BAU than in first-best), see Figure 6.

The number of hydrogen vehicles is reduced by 21% in the second-best I solution compared to the first-best solution, see Figure 7. The total number of vehicles is reduced by 8% compared to the first-best solution and are 16% higher than the BAU outcome. The size of the vehicle park in the second-best I solution are closer to the first-best solution than the BAU outcome, and the market share for electric vehicles are now 63% compared to 56% in the first-best outcome. Thus, when the technologies are close substitutes, the electric

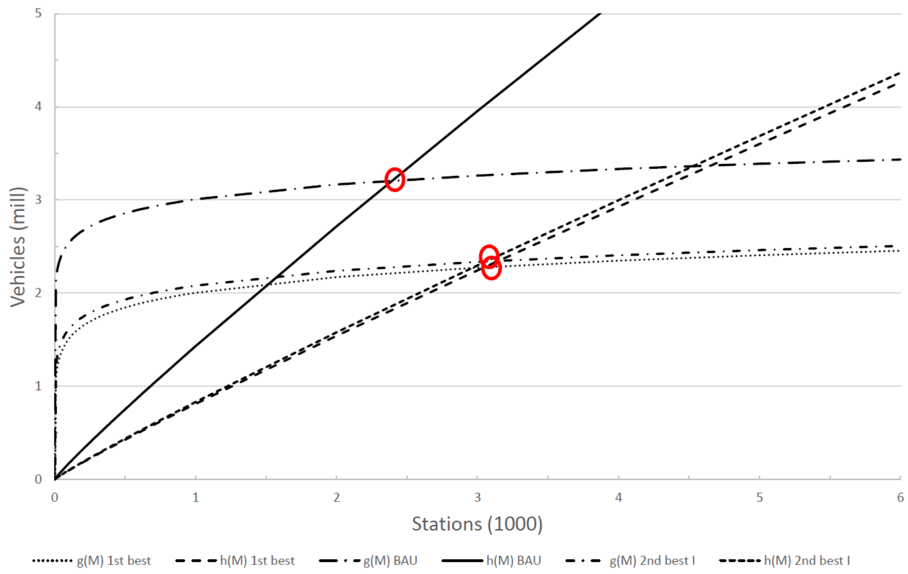

Figure 6: Graph showing the second-best I solution for the electric vehicle and station market when the two technologies are close substitutes (case A). Because of no hydrogen vehicles in BAU, the number of electric vehicles are higher in the BAU outcome than in the first-best when they are close substitutes. The first-best and the second-best I outcome for electric vehicles are very close.

vehicles are taking over some of the market from hydrogen vehicles in the second best I solution, but not as much as in the BAU outcome (which is 100%).

The annual welfare from the road transport in the second-best I solution is 1.6 billion NOK lower than in the first-best outcome, but 1.3 billion NOK higher than in the BAU outcome. Thus, the second-best I policy is an improvement over BAU, but still falls short of the first-best welfare level.

4.6.2 Second-best II (subsidies to stations and vehicles)

When vehicles may be subsidized in addition to stations, we get closer to the first-best solution. That is, the number of hydrogen vehicles increases compared to the second-best I outcome (but is still less than the first-best outcome), while the number of electric vehicles is actually somewhat lower when they are subsidized (second-best II) compared to when they are not (second-best I). This is probably due to the hydrogen vehicles becoming more competitive when subsidized and therefore lowering the number of electric vehicles. The total size of the vehicle market is only 2% lower than in the first-best outcome. The number of stations and charging/filling per vehicle change only marginally in second-best II compared to second-best I. The second-best subsidy rates to fast charging and filling stations are now respectively $\sigma_1 = 0.43$ and $\sigma_2 = 0.37$, while the subsidy rates to purchasing electric and hydrogen vehicles are respectively $u_1 = 0.023$ and $u_2 = 0.038$.

Annual welfare from the road transport in the second-best II solution is 1.4 billion NOK lower than in the first-best outcome, but 1.5 billion NOK higher than in BAU. Thus, the additional gains of subsidizing vehicles in addition to stations are 200 million NOK and thus somewhat limited.

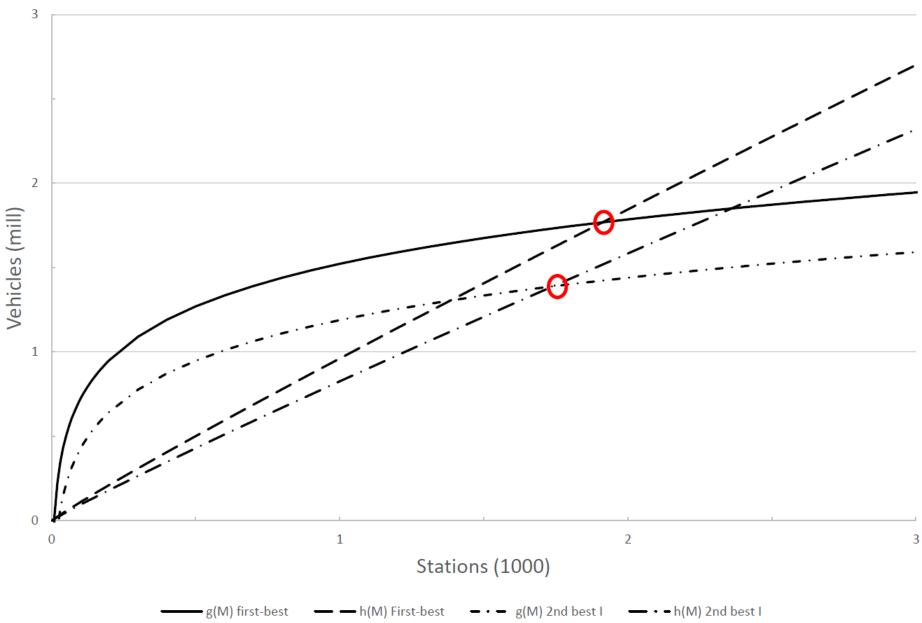

Figure 7: Graph showing the second-best I solution compared to the first-best outcome for the hydrogen market when the two technologies are close substitutes (case A). In the BAU outcome there are no hydrogen vehicles.

4.6.3 Public expenditures

The public expenditures are more than twice as high in the first-best outcome compared to the second-best I outcome. The annual subsidy payment in the first-best solution when the technologies are close substitutes is 8.6 billion NOK, while in the second-best I solution (only subsidizing stations) it is 3.7 billion NOK. Combining subsidies to both stations and vehicles (second-best II) has approximately the same public expenditures as in the first-best outcome: 8.3 billion NOK. As a comparison, total annual welfare in the road transport market is 38 billion NOK in the first-best scenario (with close substitutes). Thus, if we had added costs of collecting public funds to the welfare expression, the second-best I policy might have outperformed the first-best policy.

If the technologies are distant substitutes, the public expenditures will be higher because there will be more vehicles, charging per vehicle and stations, but also the welfare will be higher. See more details in Appendix B.

Public expenditures are lower if only electric vehicles are available than in the case with two technologies, both in the first- and second-best solutions, because then the government do not have to subsidize two station networks, either through subsidizing charging/filling or stations. Public expenditures with only electric vehicles are 6.3 billion NOK in the first-best solution, compared to 8.6 billion NOK when there are two technologies. In the second-best I solution, public expenditures are reduced from 3.7 billion to 2.8 billion NOK when there are only electric vehicles.[17]

The effects on public expenditures show that in addition to the tradeoff for the consumer between network size and product differentiation, there is also a tradeoff for the government between welfare and government budget.

[17]With only hydrogen vehicles, the public expenditures are 9.7 billion NOK in the first-best solution, and 4 billion NOK in the second-best I solution.

4.7 Sensitivity analysis

As mentioned before, many of the parameters are highly uncertain. Thus, we have performed a number of sensitivity analysis, increasing and reducing one and one parameter value, keeping the other parameters unchanged. Overall, the results are quite intuitive, such as increasing the fixed cost of fast charging stations leads to fewer stations and electric vehicles. A detailed overview of the sensitivity results are shown in Appendix D. Further, we find that the results are especially sensitive to the values of a_i, κ_i, ρ_i and β_i, and thus we focus on those parameters here.

The analysis has been done for close substitutes. First, when we increase a_1 (a_2) by 100%, the first-best solution has only electric (hydrogen) vehicles. Likewise, when we decrease a_1 (a_2) by 50%, the first-best solution has only hydrogen (electric) vehicles. Second, when κ_i changes, the numbers of vehicles and stations change in a predictable way, but the numbers are highly sensitive to the value of κ_i. When we increase κ_1 (κ_2) by 100%, the first-best solution has only electric (hydrogen) vehicles. Likewise, when we decrease κ_1 (κ_2) by 50%, the first-best solution has only hydrogen (electric) vehicles. Hence, whether there should be one or two technologies depends highly on both the direct utility of the two vehicle technologies, and the utility derived through charging/filling.

Further, the higher ρ_i, the fewer stations in the first-best solution, and the less difference between the first-best and the BAU outcome. This is intuitive since ρ_i measures the utility of more stations. If ρ_i is lower, the network effect becomes more important, and at some point it is optimal with only one technology and many stations, as the network effect dominates the benefit of having access to different types of vehicles. In our simulations, the optimal choice is then to have only hydrogen vehicles, as the benefit of these vehicles increases more with the number of stations than electric vehicles do.[18]

The numbers of vehicles and stations are also highly sensitive to the value of β_i. β_i determines the indirect utility from more stations via the total number of charging per vehicle. The higher β_i, the more the utility increases from more charges/fillings per vehicles (for a given number of stations). The sensitivity analysis suggests that a higher β_i increases the number of stations, and for sufficiently high β_i it is optimal with only electric vehicles. In this case it is not the importance of the network size that increases, as opposed to when ρ_i is reduced, which explains why we get only electric vehicles in the former case while only hydrogen vehicles in the latter case. A higher β_i also increases the welfare difference between the optimal and BAU solutions.

5 Conclusions

Whether there should be one or more technologies in a decarbonized road transport sector is an important policy question for the coming years. Our goal has been to provide insight into this question.

We have demonstrated, both theoretically and numerically, that important factors are the net utility of the vehicle itself and of charging/filling, the fixed costs of stations, and the substitutability between the vehicle technologies. Further, the market outcome for one vehicle technology depends crucially on the number of vehicles of the other technology, and critical mass may be needed to pass an unstable equilibrium. This means that if one technology has gotten a head, the other technology might not be able to get into the market, even if it is optimal to have two technologies.

Further, we have shown that the first-best solution can be realized in the market by subsidizing charging/filling. However, due to the possibility of unstable equilibria, the market may need additional policies

[18]This result hinges of course on the calibration of our model, where the calibration for hydrogen vehicles is especially uncertain.

initially to find the stable and optimal equilibrium. A second-best policy of subsidizing stations instead of charging/filling implies less than half the public cost compared to the first-best policy, and takes us close to the first-best solution. For electric vehicles very close, and for hydrogen vehicles quite close.

The numerical results in the context of the Norwegian road transport sector indicate that a combination of the two technologies, even when they are quite close substitutes, is optimal. The welfare gains going from one to two technologies are much larger if the technologies are distant than if they are close substitutes. If they are much closer substitutes, it is possible that both technologies are realized in the market (with the first-best subsidy implemented), even though it is optimal with only one technology.

The results in our study should be interpreted with caution, however, as they are derived from a quite stylized model with several uncertain parameters. Calibration of the model is highly uncertain as this is currently an emerging market. The uncertainty is both related to how the technology and the market structure will develop the next years, and the consumers' utility from owning and using the two types of vehicles. Even if first-best policies were to be implemented, it is difficult to identify the optimal subsidy rate due to the uncertainty about the crucial parameter ρ_i. It is therefore difficult to know whether a first-best policy actually has been implemented.

We have identified one particularly important factor for whether one or more technologies are optimal, that is, how close substitutes the vehicle technologies are. How the substitutability between the technologies will develop is difficult to predict, but it will likely vary across different segments of the vehicle market. Since the substitutability is of such great importance, it will be important to study this factor more closely, also in other markets where network effects and product differentiation are central.

As mentioned above, the number of vehicles of the other technology can be important for whether a new technology will get into a market. Hence, it might be difficult to identify whether a situation with first-best policies in place but only one technology in the market, means that it is in fact optimal with only one technology, or whether instead it is optimal with two technologies but the new technology is struggling to pass the unstable equilibrium.

Last but not least, we have disregarded environmental externalities in our analysis, and a future research idea is to include this into the model. Further, our model is static, and hence cannot be used to analyze the dynamic transition from a fossil-based to a non-fossil-based road transport market. Extending our model to a dynamic model studying the transition process could be valuable. Potential government interventions in order to reduce the cost and increase the performance of the technologies through technological development are also disregarded in our analysis, and could be included in a dynamic analysis.

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A Calibration

A.1 Calibration of the electric vehicle market

We calibrate the model against the Norwegian road transport market, using both current data and future projections.[19] As mentioned in the main text, we consider the calibrated equilibrium as the first best solution.

A.1.1 The number of vehicles (x_1)

Norwegian Environment Agency (2015) analyzes different packages of measures for 2030, and uses a reference level for total number of vehicles in Norway in 2030 (p. 149-150). This number is 3 585 000 vehicles and includes cars, light commercial vehicles, trucks and buses. As electric vehicles are much more prevalent today than hydrogen vehicles, we initially calibrate our model so that in the first best equilibrium the number of electric vehicles is identical to the projected number for the whole vehicle stock (and assume no hydrogen vehicles).[20]

A.1.2 The number of charges per vehicle per station (q_1)

According to Figenbaum (2019) the average charging in 2017 lasted for 20.3 minutes. We use this number and assume 20 percent utilization of the charging stations. This means 14.2 charges per charging point per day.[21] We also assume that there will be 10 charging points on average per charging station[22]. We can then calculate the total number of charges per year per station, and by dividing by the number of vehicles we derive the number of charges per vehicle per station in our calibrated equilibrium ($q_1 = 0.014$).

A.1.3 The price of one charge (ω_1)

At some stations in Norway customers pay for charging per minute. At other stations customers pay for per minute and kWh. In the calibration we have used the prices of the provider of fast charging stations that has the highest market share, Fortum Charge & Drive. The price is 3.10 NOK per minute (Norwegian Electric Vehicle Association, 2019b). According to Figenbaum (2019), the average charge in 2017 lasted for 20.3 minutes. For 20.3 minutes, this is 62.93 NOK per charge, and this is the value of ω_1. The prices for fast charging might change in the future, but we use the prices of today.[23]

A.1.4 The fixed annual cost of a charging station (f_1)

We assume that one charging point costs 800 000 NOK, everything included.[24] With 10 charging points per charging station (see above), and an interest rate of 10 % and 10 years lifetime, the fixed annual cost of a charging station is 1.3 million NOK.

[19]In Norway there are over 200 000 electric vehicles and electric cars constitutes 7.2 % of the total car park (Norwegian Electric Vehicle Association, 2019a), which gives some data into the calibration.

[20]Obviously, it will not be 3.6 million electric vehicles in Norway in 2030, but we are interested in a long-run equilibrium with only non-fossil vehicles. It will take more years to reach that equilibrium.

[21]According to Sales & Product Manager Snorre Sletvold at Fortum Charge & Drive they need 10-12 charges per day in order to not loose money.

[22]On average, Tesla currently has 13 charging points per charging station in Norway, while the other fast charging network for other electric vehicle models has 2.24 charging points per charging station, according to Nobil (2019).

[23]How much can a vehicle drive on one charge? According to Figenbaum (2019), the average charge in 2017 gave 9.6 kWh energy. Given larger batteries, it is reasonable to assume that the energy delivered to each vehicle per minute of charging will increase. If energy per charging is 2.5 times higher than today, while charging lasts the same amount of time, one charge will take the vehicle 100 km, assuming that vehicles spend 2.5 kWh per 10 km (Norwegian Electric Vehicle Association, 2017).

[24]This is somewhat higher than for instance Fortum Charge & Drive's fixed cost of 50 kW stations which is 600-650 000 NOK, but with higher effect, the costs might increase somewhat.

A.1.5 The unit cost of each charge (ψ_1)

We use equation (8) and the numbers derived above (for f_1, q_1, x_1 and ω_1) to determine ψ_1, which then becomes 37.79 NOK. According to Sales & Product Manager Snorre Sletvold at Fortum Charge & Drive, the unit cost is 3-3.5 NOK/kWh (excl. VAT). If we use the energy that an average charge gave in 2017 (9.6 kWh), this means that the unit cost of one charge is 36-42 NOK. This means that a value of $\psi_1 = 37.79$ seems realistic. In the future there will be more energy per charge, but then probably the price will change as well.

A.1.6 The number of charging stations (M_1)

We assume that the number of charging stations per vehicle is the same as the current number of Tesla cars per Tesla charging station in Norway today, which in 2019 were 721.[25] Combining this with the number of vehicles, we get 4975 fast charging stations in our calibrated first-best equilibrium.

A.1.7 The price of the vehicle (p_1)

In our model, there is just one type of electric (and hydrogen) vehicle, which should represent everything from small electric vehicles to large trucks. Hence, it is natural to think of the price per vehicle as a rough average of all these. For this purpose, we use the price of the cheapest trim of Tesla Model Y in June 2019, which is 450 320 NOK (OFV, 2019). This price is exempted from VAT as electric vehicles are exempted from VAT in Norway. Further, we assume an interest rate of 5 % and a vehicle lifetime of 15 years. This gives an annual price of 43 385 NOK. Adding VAT would increase the price by 25 %. On the other hand, battery costs are projected to fall the coming years. Hence, we stick to this price in our model, but consider this as the price incl. VAT.

A.1.8 The degree the stations with the same technology can substitute each other (ρ_1)

The size of ρ_1 follows from the relationship $\rho_1 = \frac{\psi_1}{\omega_1} = 0.6$.

A.1.9 The indirect utility from more stations (β_1)

The size of β_1 is highly uncertain, except that we have required $\beta < \frac{\rho}{2-\rho}$. A positive β_1 implies that the elasticity of demand for charging is below -1 (when keeping the number of stations fixed), and the higher β_1 the more elastic demand. Therefore, we believe that β_1 should not be too high. In lack of good guidelines to determine the value of β_1, we simply assume that $\beta_1 = 0.1$. In the robustness section we discuss the results of changing the values for β_i.

A.1.10 The utility from the charging network (κ_1)

Before calibrating the utility we normalize x_i to million vehicles, M_i to 1,000 stations, and normalize prices and costs so that utility and welfare is measured in billion NOK.[26] Based on the values of parameters and variables determined above, we can calibrate κ_1 based on equation (5), giving $\kappa_1 = 32$.

[25] Note that this is vehicles per charging station, not per charging point.

[26] The price of vehicles is measured in 1,000 NOK, while the cost of stations is measured in million NOK.

A.1.11 The utility of the first vehicle (a_1)

We set $a_1 = p_1$ because this is a benchmark that make electric vehicles in between case I and III assuming there are no hydrogen vehicles.

A.1.12 The parameter that determines the price sensitivity of demand (b_1)

Finally, based on equation (4) and the other values already determined, we derive $b_1 = 6.8$.[27]

A.1.13 The substitutability between hydrogen and electric vehicles (ϕ)

With no hydrogen vehicles in the calibrated equilibrium, the value of ϕ is irrelevant. However, for subsequent simulations we investigate two cases for ϕ. Case A: the technologies are close substitutes and ϕ_A is equal to 4.5, i.e., $\frac{2b_i}{3}$. Case B: the technologies are distant substitutes and ϕ_B is equal to 2.3, i.e., $\frac{b_i}{3}$.

A.2 Calibration of the hydrogen vehicle market

The parameter values for the hydrogen vehicle market is even more uncertain than for the electric vehicle market. Where we don't have reasons to believe that they are different, we assume the same values for hydrogen as for electric vehicles in the initial calibration. These are the following:

- $b_1 = b_2$
- $\beta_1 = \beta_2$
- $p_1 = p_2$

We will however vary some of these (and other) parameter values in the sensitivity analysis. For the fixed and operating costs of hydrogen stations, we use specific data and information to derive cost estimates for these stations. From this information we calculate ρ_2. For the remaining utility parameters (a_2 and κ_2) we initially choose numbers so that a first-best equilibrium with only hydrogen vehicles would give the same numbers of vehicles as in the electric vehicle first-best equilibrium calibrated above.

A.2.1 The fixed annual cost of a hydrogen station (f_2)

Hydrogen can be produced using electricity and water in an electrolyzer, which can be done on-site. The fixed cost of a hydrogen station that is currently build is in the range 17-25 million NOK (Enova, 2019). These costs are assumed to fall, but by how much is uncertain. Assuming a cost of 15 million NOK, 10 % interest rate and 10 years lifetime, the annual fixed cost becomes 2.44 million NOK.

A.2.2 The unit cost of one hydrogen filling lasting for 100 km (ψ_2)

The hydrogen vehicle Toyota Mirai can drive approximately 100 km per kg of hydrogen (US Department of Energy, 2019). Producing 1 kg of hydrogen uses approximately 50 kWh of electricity, and about 15 kWh more for compression and cooling, according to information from the hydrogen company NEL.[28] Future

[27] To get a better understanding of what the calibration implies for the utility of electric vehicles, it is useful to compute the gross contribution to utility of respectively owning a vehicle and charging a vehicle (i.e., before subtracting the costs of buying and charging). That is, the second and third parts of the utility function in equation (3). With the calibrated values, the second part (utility of owning) amounts to 112 billion NOK, while the third part (utility of charging) amounts to 97 billion (this corresponds to about 22,000 NOK per capita and 19,000 NOK per capita, i.e., 2,200 Euro and 1,900 Euro, respectively per year). This means that the utility of owning the electric vehicle is approximately as important as the utility of charging via the fast charging network.

[28] Personal communication with VP Investor Relations & Corporate Communication, Bjørn Simonsen.

electricity prices are uncertain, and we assume 0.8 NOK per kWh (about 80 Euro per MWh), including grid tariffs. Adding VAT (25%), we derive $\psi_2 = 65$ NOK per 100 km of driving.

A.2.3 The price of one filling lasting for 100 km (ω_2)

The price of hydrogen on hydrogen stations in Norway has been 90 NOK/kg incl. VAT, but this is below the unit cost at the moment. One hydrogen station owner has notified that the price will increase to around 100 NOK/kg (E24, 2019b). This price might change in the future, but we choose $\omega_2 = 100$.

A.2.4 The degree the stations with the same technology can substitute each other (ρ_2)

The size of ρ_2 follows from the relationship $\rho_2 = \frac{\psi_2}{\omega_2} = 0.65$. Thus, ρ_2 is slightly higher than ρ_1.

A.2.5 The utility of the first vehicle (a_2)

It seems reasonable to assume that the utility of the first hydrogen vehicle is lower than the utility of the first electric vehicle because the hydrogen vehicle can not be filled at home and is therefore more dependent on the station network, similar to the gasoline and diesel vehicle technology we are familiar with. We therefore assume that $a_2 < a_1$ and we set $a_2 = 0.5 * p = 21.7$

A.2.6 The utility of the station network (κ_2)

As hydrogen vehicles are more dependent on the station network than electric vehicles, it is reasonable to assume $\kappa_2 > \kappa_1$. We calibrate κ_2 so that $x_2 = x_1$ in the first-best scenario when there are only hydrogen vehicles in the market. $\kappa_2 = 61$.

With this set of parameters, a first-best equilibrium with only hydrogen vehicles would give $x_2 = 3.585$, $M_2 = 4.054$ and $q_2 = 0,019$.

B Numerical analysis – appendix material

B.1 The road transport market with only hydrogen technology

When comparing the first-best solution with the BAU outcome, we find that also for hydrogen vehicles total filling is reduced substantially when filling is no longer subsidized. Even though the subsidy rate to hydrogen filling is lower than to charging ($\rho_2 > \rho_1$), total filling per vehicle is reduced by 69% (compared to 47% for electric vehicles). This is a result of both the number of stations (-50%) and the filling per station per vehicle (-37%) being reduced. More expensive filling and fewer filling stations reduce the demand for hydrogen vehicles by 16%. Welfare in the road transport market is reduced by 9%. Also in BAU the unstable equilibrium is very small and is therefore not too difficult to pass.

B.2 The technologies being distant substitutes

In this section we will present the analysis done in section 4 with the technologies being distant substitutes.

B.2.1 Interactions between technologies – first-best

When the two technologies are *distant* substitute, the numbers of electric and hydrogen vehicles are reduced by less than when they are close substitutes. Thus, there are more vehicles in total when the products are distant substitutes. The total number of vehicles in the first-best solution increases by 45% compared to when there is only one technology, compared to 29% when they are close substitutes. This is as expected – the size of the market increases when there is more variety to choose from. The market share of electric vehicles is now 51%, thus an almost equal split of the market. The number of stations decrease less when the technologies are distant substitutes, as the number of vehicles is also less reduced. Charging/filling per vehicle still does not change much, while charging/filling per station per vehicle increase less than in case A.

Similar to when the technologies are close substitutes, electric vehicles move from being in case I to being in case II, while hydrogen vehicles stay in case II. Thus, even when the technologies are distant substitutes, there is a risk that electric vehicles might not get a foothold into the market if there are many hydrogen vehicles already.

The annual welfare in the road transport sector increases by 12.7 billion NOK (+34%) compared to the case with only electric vehicles, and by 16.1 billion NOK (+47%) compared to the case with only hydrogen vehicles. Thus, when the technologies are distant substitutes, there is a substantial welfare gain from having two instead of one technology.

B.2.2 Interactions between technologies – comparing BAU and first-best

When the technologies are distant substitutes, the market shares only change slightly in BAU compared to the first-best outcome. The market share of electric vehicles increases from 51% in the first-best solution to 55% in the BAU outcome. The number of electric vehicles falls by 7%, while the number of hydrogen vehicles falls by 21%. Thus, the total number of vehicles drops by 14%.

Charging/filling per vehicle is reduced by 41-47%. The number of hydrogen stations decreases by 53%, while the number of fast charging stations declines by 51%. Hence, charging and filling per vehicle per station increases somewhat. The percentage reduction in annual welfare is the same as in case A, i.e., 8%.

B.2.3 Second-best solutions

Second-best I (subsidy to stations): When the two technologies are distant substitutes, the number of electric vehicles in the second-best I solution is quite close to both first-best and BAU, see Figure 9. The number of hydrogen vehicles is almost 300 lower than in first-best and 200 higher than in BAU. The total number of vehicles is reduced by 8% compared to first-best, but 7% higher than in BAU. The second-best subsidy rates to fast charging and filling stations are respectively $\sigma_1 = 0.44$ and $\sigma_2 = 0.43$, i.e., very close the subsidy rates in Case A.

As we can see from Figure 9, the number of fast charging stations is almost the same as in first-best, and much bigger than in BAU (almost 1,700 stations more). The same applies for hydrogen stations. This reflects that in the second-best I scenario the stations are subsidized, and therefore the numbers of stations are close to the optimal number. In contrast, charging/filling per vehicle is reduced by 36-47%, as charging/filling is no longer subsidized. The annual welfare from the road transport in the second-best I solution is reduced by 2.1 billion NOK compared to the first-best outcome, and is 1.7 billion NOK higher than in the BAU outcome. Hence, also in this case we see that the second-best I policy is a clear improvement over BAU, but still somewhat far from first-best.

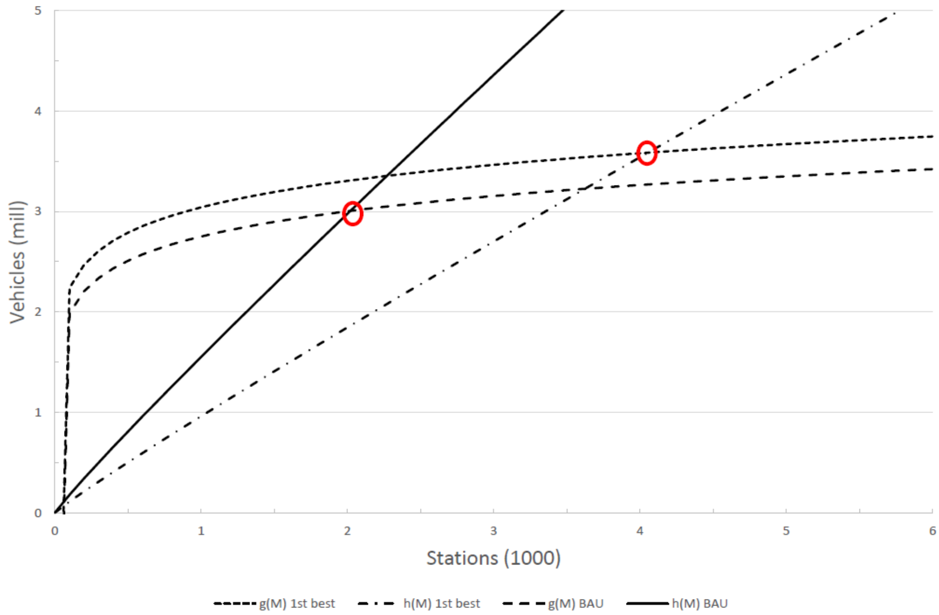

Figure 8: First-best and BAU equilibrium with only hydrogen vehicles in the market.

Second-best II (subsidies to stations and vehicles): When also the vehicles may be subsidized, the number of vehicles in the second-best II solution is even closer to the first-best solution than in the second-best I solution. The total number of vehicles is now only 2% lower than in the first-best outcome. The results for the numbers of stations and charging/filling per vehicle are approximately the same as in the second-best I-solution. The second-best subsidy rates to fast charging and filling stations are now respectively $\sigma_1 = 0.43$ and $\sigma_2 = 0.37$, while the subsidy rates to purchasing electric and hydrogen vehicles are respectively $u_1 = 0.023$ and $u_2 = 0.038$, which is identical to the vehicle subsidy in case A.

The annual welfare from the road transport in the second-best II solution is reduced by 1.9 billion NOK compared to the first-best outcome, and is 1.9 billion NOK higher than in BAU. Thus, also in this case the additional gains of subsidizing vehicles in addition to stations is somewhat limited.

Public expenditures: Also when the technologies are close substitutes, the public expenditures are more than twice as high in the first-best outcome compared to the second-best I outcome. Total expenditures for the government are higher when the technologies are distant substitutes, as the total market is larger. The subsidy payment in the first-best solution is 11.6 billion NOK, while in second-best I it is 4.8 billion NOK, and in second-best II it is 11.1 billion NOK.

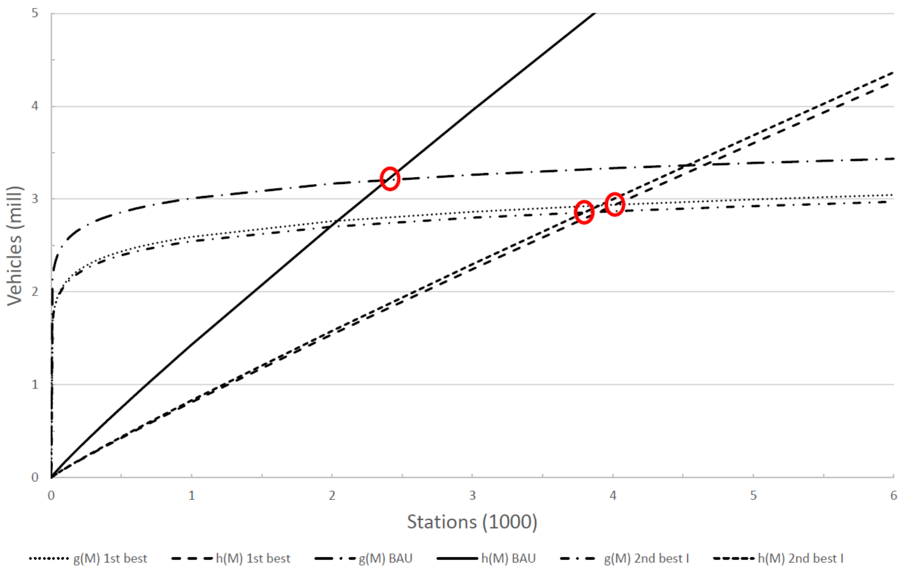

Figure 9: Graph showing how close the second-best I solution for the electric vehicle and station market is to the first-best solution when the two technologies are distant substitutes (case B).

C Results from the numerical analysis

Only electric vehicles														
	First-best	BAU	Second-best I	Second-best II	Diff BAU vs. first-best	Percentag e diff BAU vs. first-best	Diff second-best I vs. first-best	Percentag e diff second-best I vs. first-best	Diff second-best I vs. BAU	Percentag e diff second-best I vs. BAU	Diff second-best II vs. first-best	Percentag e diff second best II vs. first-best	Diff second-best II vs. BAU	Percentag e diff second best II vs. BAU
x1	3.585	3.209	3.379	3.530	-0.376	-10 %	-0.206	-6 %	0.170	5 %	-0.055	-2 %	0.321	10 %
M1	4.975	2.394	4.812	4.823	-2.581	-52 %	-0,163	-3 %	2.418	101 %	-0.152	-3 %	2.429	101 %
q1	0.014	0.016	0.008	0.008	0.002	14 %	-0.006	-43 %	-0.008	-50 %	-0.006	-43 %	-0.008	-50 %
M1q1	0.070	0.038	0.038	0.039	-0.031	-45 %	-0.031	-45 %	0.000	1 %	-0.031	-45 %	0.000	1 %
W	37.328	35.101	36.110	36.187	-2.227	-6 %	-1.219	-3 %	1.009	3 %	-1.142	-3 %	1.086	3 %
s1	0.4	0	0	0	--	--	--	--	--	--	--	--	--	--
σ1	0	0	0.448	0.425	--	--	--	--	--	--	--	--	--	--
u1	0	0	0	0.024	--	--	--	--	--	--	--	--	--	--
Only hydrogen vehicles														
	First-best	BAU	Second-best I	Second-best II	Diff BAU vs. first-best	Percentag e diff BAU vs. first-best	Diff second-best I vs. first-best	Percentag e diff second-best I vs. first-best	Diff second-best I vs. BAU	Percentag e diff second-best I vs. BAU	Diff second-best II vs. first-best	Percentag e diff second best II vs. first-best	Diff second-best II vs. BAU	Percentag e diff second best II vs. BAU
x2	3.585	3.006	3.254	3.506	-0.579	-16 %	-0.331	-9 %	0.248	8 %	-0.079	-2 %	0.500	17 %
M2	4.054	2.020	3.905	3.918	-2.034	-50 %	-0.149	-4 %	1.885	93 %	-0.136	-3 %	1.898	94 %
q2	0.019	0.012	0.012	0.012	-0.007	-37 %	-0.007	-37 %	0	0 %	-0.007	-37 %	0	0 %
M2q2	0.077	0.024	0.047	0.047	-0.053	-69 %	-0.030	-39 %	0.023	93 %	-0.030	-39 %	0.023	94 %
W	33.915	30.789	32.122	64.672	-3.126	-9 %	-1.793	-5 %	1.333	4 %	30.757	91 %	33.883	110 %
s2	0.35	0	0	0	--	--	--	--	--	--	--	--	--	--
σ2	0	0	0.417	0.374	--	--	--	--	--	--	--	--	--	--
u2	0	0	0	0.039	--	--	--	--	--	--	--	--	--	--

Figure 10: Results from the numerical analysis for only electric vehicles in the market and for only hydrogen vehicles. x_i is in million, M_i is in 1000, q_i is in number of charges/fillings per year per vehicle per station,W is in billion NOK.

Two technologies. Close substitutes. Phi= 4,545														
	First-best	BAU	Second-best I	Second-best II	Diff BAU vs. first-best	Percentage diff BAU vs. first-best	Diff second best I vs. first-best	Percentage diff second best I vs. first-best	Diff second-best I vs. BAU	Percentage diff second-best I vs. BAU	Diff second best II vs. first-best	Percentage diff second best II vs. first-best	Diff second best II vs. BAU	Percentage diff second best II vs. BAU
x1	2.278	3.209	2.342	2.309	0.931	41 %	0.064	3 %	-0.867	-27 %	0.031	1 %	-0.900	-28 %
x2	1.768	0	1.390	1.655	-1.768	-100 %	-0.378	-21 %	1.390	--	-0.113	-6 %	1.655	--
x1+x2	4.046	3.209	3.732	3.964	-0.837	-21 %	-0.314	-8 %	0.523	16 %	-0.082	-2 %	0.755	24 %
M1	3.049	2.394	3.062	3.050	-0.655	-21 %	0.013	0 %	0.668	28 %	0.001	0 %	0.656	27 %
M2	1.912	0	1.741	1.763	-1.912	-100 %	-0.171	-9 %	1.741	--	-0.149	-8 %	1.763	--
q1	0.023	0.016	0.013	0.013	-0.007	-30 %	-0.010	-43 %	-0.003	-19 %	-0.010	-43 %	-0.003	-19 %
q2	0.039	0	0.027	0.026	-0.039	-100 %	-0.012	-31 %	0.027	--	-0.013	-33 %	0.026	--
q1M1	0.070	0.038	0.040	0.040	-0,032	-45 %	-0.030	-43 %	0.002	4 %	-0.030	-43 %	0.001	4 %
q2M2	0.075	0	0.047	0.046	-0.075	-100 %	-0.028	-37 %	0.047	--	-0.029	-39 %	0.046	--
W	38.032	35.100	36.398	36.593	-2.932	-8 %	-1.634	-4 %	1.298	4 %	-1.439	-4 %	1.493	4 %
s1	0.4	0	0	0	--	--	--	--	--	--	--	--	--	--
s2	0.35	0	0	0	--	--	--	--	--	--	--	--	--	--
σ1	0	0	0.419	0.425	--	--	--	--	--	--	--	--	--	--
σ2	0	0	0.468	0.374	--	--	--	--	--	--	--	--	--	--
u1	0	0	0	0.023	--	--	--	--	--	--	--	--	--	--
u2	0	0	0	0.038	--	--	--	--	--	--	--	--	--	--

Figure 11: Results from the numerical analysis for the two network technologies when they close substitutes. x_i is in million, M_i is in 1000, q_i is in number of charges/fillings per year per vehicle per station,W is in billion NOK.

Two technologies. Distant substitutes. Phi= 2.272														
	First-best	BAU	Second-best I	Second-best II	Diff BAU vs. first-best	Percentage diff BAU vs. first-best	Diff second best I vs. first-best	Percentage diff second best I vs. first-best	Diff second-best I vs. BAU	Percentage diff second-best I vs. BAU	Diff second best II vs. first-best	Percentage diff second best II vs. first-best	Diff second best II vs. BAU	Percentage diff second best II vs. BAU
x1	2.646	2.465	2.544	2.616	-0.181	-7 %	-0.102	-4 %	0.079	3 %	-0.030	-1 %	0.151	6 %
x2	2.560	2.032	2.268	2.490	-0.528	-21 %	-0.292	-11 %	0.236	12 %	-0.070	-3 %	0.458	23 %
x1+x2	5.206	4.497	4.812	5.106	-0.709	-14 %	-0.394	-8 %	0.315	7 %	-0.010	-2 %	0.609	14 %
M1	3.584	1.800	3.486	3.490	-1.784	-50 %	-0.098	-3 %	1.686	94 %	-0.094	-3 %	1.690	94 %
M2	2.833	1.332	2.711	2.722	-1.501	-53 %	-0.122	-4 %	1.379	104 %	-0.111	-4 %	1.390	104 %
q1	0.020	0.021	0.011	0.011	0.001	5 %	-0.009	-45 %	-0.010	-48 %	-0.009	-45 %	-0.010	-48 %
q2	0.027	0.034	0.018	0.018	0.007	26 %	-0.009	-33 %	-0.016	-47 %	-0.009	-33 %	-0.016	-47 %
q1M1	0.072	0.038	0.038	0.038	-0.034	-47 %	-0.033	-47 %	0.001	1 %	-0.033	-46 %	0.001	2 %
q2M2	0.076	0.045	0.049	0.049	-0.031	-41 %	-0.028	-36 %	0.004	8 %	-0.027	-36 %	0.004	8 %
W	50.004	46.160	47.858	48.078	-3.844	-8 %	-2.146	-4 %	1.698	4 %	-1.926	-4 %	1.918	4 %
s1	0.4	0	0	0	--	--	--	--			--	--	--	--
s2	0.5	0	0	0	--	--	--	--			--	--	--	--
σ1	0	0	0.440	0.425	--	--	--	--			--	--	--	--
σ2	0	0	0.428	0.374	--	--	--	--			--	--	--	--
u1	0	0	0	0.023	--	--	--	--			--	--	--	--
u2	0	0	0	0.038	--	--	--	--			--	--	--	--

Figure 12: Results from the numerical analysis for the two network technologies when they are distant substitutes. x_i is in million, M_i is in 1000, q_i is in number of charges/fillings per year per vehicle per station,W is in billion NOK.

Costs first best	Costs second best I	Costs second best II
Two technologies. Close substitutes. Phi= 4,545		
8.6	3.7	8.3
Two technologies. Distant substitutes. Phi= 2,272		
11.6	4.8	11.3
Only electric vehicles		
6.3	2.8	6.3
Only hydrogen vehicles		
9.7	4.0	9.5

Figure 13: Results from the numerical analysis of the public costs. Numbers in billion NOK.

D Results sensitivity analysis

phi=4,545	Parameter	New values	x1, first-best	x2, first-best	M1, first-best	M2, first-best	W, first-best	W, BAU	Delta W
Result base-case	--	--	2.278	1.768	3.049	1.912	38.032	35.100	2.932
Increase by 100%	f1	2.603926	1.675	2.275	1.035	2.499	35.737	34.087	1.650
Reduce by 50%	f1	0.650982	3.038	1.051	8.795	1.099	41.339	39.587	1.752
Increase by 100%	f2	4.88236	3.585	0	4.975	0	37.328	35.101	2.227
Reduce by 50%	f2	1.22059	1.477	2.795	1.909	6.500	42.388	38.839	3.549
Increase by 100%	p	86.77	0	0	0	0	0		
Reduce by 50%	p	21.692	4.050	4.128	5.675	4.710	171.094	165.247	5.847
Increase by 100%	kappa1	63.51196	8.851	0	30.325	0	227.544	213.970	13.574
Reduce by 50%	kappa1	15.87799	0	3.585	0	4.054	33.915	5.758	28.157
Increase by 100%	kappa2	122.57	0	13.524	0	37.747	531.249	35.101	496.148
Reduce by 50%	kappa2	30.643	3.585	0	4.975	0	37.328	35.101	2.227
Increase by 100%	b	13.634	1.275	1.128	1.629	1.184	21.261	19.579	1.682
Reduce by 50%	b. NB. Here phi=2.272	-3.409	4.217	4.570	5.929	5.247	89.161	81.944	7.217
Increase by 100%	a1	86.77	10.263	0	15.490	0	338.861	332.354	6.507
Reduce by 50%	a1	21.692	0	3.585	0	4.054	33.915	30.789	3.126
Increase by 100%	a2	43.384	0	7.066	0	8.342	149.815	143.962	5.853
Reduce by 50%	a2	10.846	3.585	0	4.975	0	37.328	35.101	2.227
Increase by 100%	psi1	75.58	1.382	2.512	1.636	2.777	34.897	31.784	3.113
Reduce by 50%	psi1	18.895	3.924	0	5.960	0	44.724	42.056	2.668
Increase by 100%	psi2	130	3.585	0	4.975	0	37.328	35.101	2.227
Reduce by 50%	psi2	32.5	0	4.242	0	5.262	48.487	44.247	4.24
	rho	0.9	2.125	1.539	0.433	0.326	36.974	36.871	0.103
	rho	0.7	2.082	1.774	1.695	1.497	36.433	34.716	1.717
	rho	0.45	0	6.339	0	22.888	81.089	43.388	37.701
	rho	0.3	0	32.444	0	836.839	1545.047	0.166	1544.881
	beta	0.4	395.214	0	362770	0	59180.272	923.618	58256.654
	beta	0.3	5.168	0	39.873	0	39.113	22.815	16.298
	beta	0.2	3.557	0	11017	0	28.771	5.271	23.500
	beta	0.05	1.731	3.057	1.196	1.788	60.186	58.513	1.673

Figure 14: Results from the sensitivity analysis. x_i is in million, M_i is in 1000, q_i is in number of charges/fillings per year per vehicle per station and W is in billion NOK.