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Compatibility Choice In the Electric Vehicle- and Charging Market

Mats Kristoffersen



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Valg av kompatibilitet i elbil- og lademarkedet.

Mats Kristoffersen

Elbilen har blitt en av de potensielle løsningene for å kunne redusere utslippene fra transportsektoren. Siden starten av dette tiåret har antallet elbiler og installerte ladestasjoner økt raskt. På samme tid har flere nye elbilprodusenter entret markedet med nye ladeteknologier. Dette har ført til høy konkurranse. Ikke bare blant elbiler, men også mellom deres tilhørende ladenettverk. En elbil er ikke lenger kompatibel med alle ladestasjoner. Den er kun kompatibel med de som støtter ens egen ladeteknologi. Dette reduserer konsumentenes lademuligheter, og dermed deres nytte av elbiler.

I denne oppgaven analyserer jeg hvordan elbilprodusentens valg av ladeteknologi påvirker diffusjonen av elbiler. Ikke overraskende fører full kompatibilitet, hvor alle elbiler kan benytte seg av alle ladestasjoner, til det høyeste antallet elbiler. Dette ser også ut til å maksimere den sosiale velferden, men det er ikke det vi observerer i markedet. For å se nærmere på dette sammenligner jeg elbilprodusentens- og samfunnets incentiver for kompatibilitet. Ved hjelp av numeriske simuleringer viser jeg at elbilprodusentene ikke har tilstrekkelig incentiv for å oppnå kompatibilitet. Jeg finner også at de i visse tilfeller foretrekker inkompatibilitet.

COMPATIBILITY CHOICE

In the Electric Vehicle- and Charging Market

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Master of Philosophy in Economics

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November 2016

Compatibility Choice

In the Electric Vehicle- and Charging Market

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Preface

I would like to thank my supervisor Mads Greker for great guidance. He has provided valuable comments and ideas throughout this process, as well as letting me take part in the research project: Electrification of Transportation. The inclusion in this project gave me the opportunity to present my findings at a seminar. I am grateful for all the inputs I got both during and after this seminar. I would also like to thank my friends for support, proofreading and fruitful discussions, you know who you are.

Abstract

The electric vehicle (EV) has become a potential solution for reducing greenhouse gas emissions from the transport sector. Since the beginning of this decade, the number of EVs and installed charging stations has increased rapidly. At the same time, several EV manufacturers have entered the market with new charging technologies. This has led to intense competition, not only among EVs, but also among their associated charging networks. Each EV is no longer compatible to all charging stations, but only those that support its charging technology. This affects the consumers' utility of an EV, and ultimately the manufacturers' sales. In this thesis, I analyze how the EV manufacturers' choice of compatibility with respect to charging technology affects the diffusion of EVs. Not surprisingly, complete compatibility where all EVs can use all charging stations, leads to the greatest amount of EVs. This seems to maximize social welfare, but may very well not be the realized market outcome. To address this matter I compare the private and social incentives for achieving compatibility. The individual manufacturers are not only shown to have inadequate incentives for compatibility, but also that they can favor incompatibility.

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CHAPTER 1

Introduction

With time, people and especially policy makers have acknowledged the threats related to climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the rapid growth in greenhouse gas (GHG) emissions will cause the temperature to rise above the two-degree target. The majority of climate research agrees that a temperature increase above two degrees will have serious and irreversible consequences. Since this problem is very much a global one, it requires the broadest possible cooperation among all countries. The United Nations has become the central organ for such cooperation. Once a year they hold a conference on climate change on the framework of the United Nations Framework Convention on Climate Change (UNFCCC). The last climate conference were held in Paris, and led to an agreement known as the: Paris Agreement. It was negotiated by 195 countries and sealed in December 2015. The agreement shall be affective from 2020 and include all countries. The aim of the agreement is to hold the global average temperature well below 2 degrees, above pre-industrial levels. In order to reach this target, all participating countries have to make national plans on how they are going to contribute. These plans must include ambitious emission reduction targets, and in particular how the countries plan to reach these targets. Every five years, each country has to set up new and more ambitious targets.

In order to form a foundation for the negotiations on the climate conference in Paris, all countries were to send in their commitments for domestic emission cuts. Norway committed themselves to reduce their 1990-emission level with 40 % within 2030. In 2015 Norway emitted 53,9 million tons of CO_2 equivalents, which

is a bit more than what we emitted in 1990. Compared to the 2015-level, Norway has to reduce their emissions by 42,3 %.

The cuts will be made together with EU. As of today, Norway is already a part of EU's Emissions Trading System (EU ETS). EU ETS is a quota system for the sectors with the highest level of emissions. Most relevant for Norway are the industrial companies, the aviation industry and the energy- and petroleum industry. Every year a set of allowances are distributed, and the different companies and institutions can trade them with one another. When emitting less than what is permitted by its allowances, one can sell the excess allowances, and conversely when emitting more than permitted, one have to buy additional ones. This ensures that the reductions will take place where they are the most cost efficient. In order to make sufficient cuts in emissions, the set of allowances is reduced from year to year.

The EU ETS accounts for 50 % of the emissions both in Europe and in Norway. The other half of Norway's emissions mostly come from: agriculture, waste, transport and construction. Cuts in these sectors, will also be made together with EU. However, a larger share of these cuts have to be made in each individual country. EU's Climate Commission has made reduction targets for all participating countries. The reduction targets are based on GDP level, and each country's respective costs of reductions. In July 2016, the targets were dealt out. Norway was handed the target of 40 % less emissions in non-ETS sectors within 2030, compared to 2005-levels. Most of the reductions have to take place in Norway, but it has been stated that some of them can be made in other countries: "Norway will fulfill its climate target through a mix of efforts at home and cuts in other European countries, but we must be prepared to take the majority of cuts at home", says the Climate and Energy Minister of Norway Vidar Helgesen.¹

¹<https://www.regjeringen.no/no/aktuelt/the-eu-proposes-climate-targets-for-norway/id2508071/>

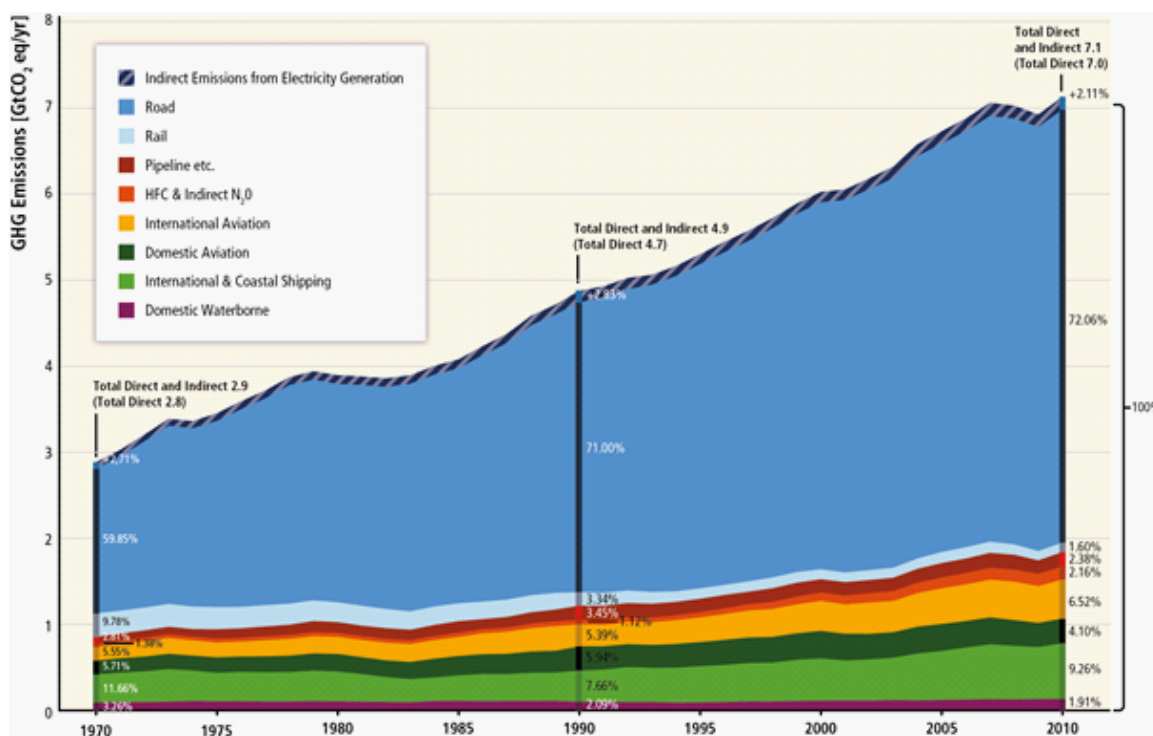


Figure 1.1. Emissions from the transport sector category by category.

The transport sector is the non-ETS sector with the highest level of GHG-emissions in Norway. The Norwegian Environment Agency reported that the transport sector was responsible for 31 % of all GHG emissions in Norway, in 2014.² This number is higher for Norway than for the world as a whole. IPCC reported in their mitigation report of 2014, that the transport sector was responsible for approximately 23 % of total energy related CO₂ emissions in the world, in 2010 (IPCC, 2014).

A substantial part of emissions from transport are related to conventional car use. Figure 1.1 is taken from the mentioned IPCC report. It shows the emissions from the transport sector divided into nine different categories of transportation. Transportation made on road is by far the largest contributor, responsible for 72,06

²<http://www.miljostatus.no/tema/klima/norske-klimagassutslipp/utslipp-av-klimagasser-fra-transport/>

% of total transport emissions. It is also the category which has increased the most in total emissions from 1970 until 2010.

1.1. The EV- and Charging Market

It is clear that significant emission cuts have to be made in the transport sector. One way the Norwegian government plan to do this, is by transforming the car fleet to mainly consist of zero-emission vehicles within 2030. In 2016 they agreed upon the target that all cars sold in Norway after 2025 should be low- and zero emission vehicles.³ Accordingly, the government have made several policy measures in order to make the electric vehicle (EV) feasible. By some referred to as the EV-initiative. And it may seem like all the exemptions and incentives for having an EV just got in place. However, Norwegian politicians have been positive to electric vehicles for a long time.

Already in the 90s they implemented incentives such as tax reductions and free parking. At that time, it was only some Norwegian brands, and not many real substitutes to the conventional car. In 2001, electric vehicles were exempted from the value added tax, and in 2005 they were allowed to drive permanently in the bus lanes. In 2009 the government started to subsidize the building of charging infrastructure (Figenbaum and Kolbenstvedt, 2013). But things did not really start to happen before the big car companies came on the EV-stage in 2010. Since that time the EV market has grown rapidly.

Figure 1.2 displays the amount of registered EVs from year to year. By the end of 2015, 68 516 EVs were registered in Norway, up from 1691 in 2008. A rather steep growth, which does not seem to slow down. Of all the new cars sold in 2015, 17,1 % were electric, in comparison to 12,5 % in 2014.⁴ With over 2,5 million registered vehicles in Norway, the fraction is still small at only 2,6 %.⁵ However, the high sales numbers suggest that this is about to change.

³<https://hoyre.no/aktuelt/nyheter/2016/naa-begynner-det-gronne-skattesiftet/>

⁴<http://www.ofvas.no/aktuelt-3/bilsalget-i-2015-article567-622.html>

⁵<https://www.ssb.no/bilreg>

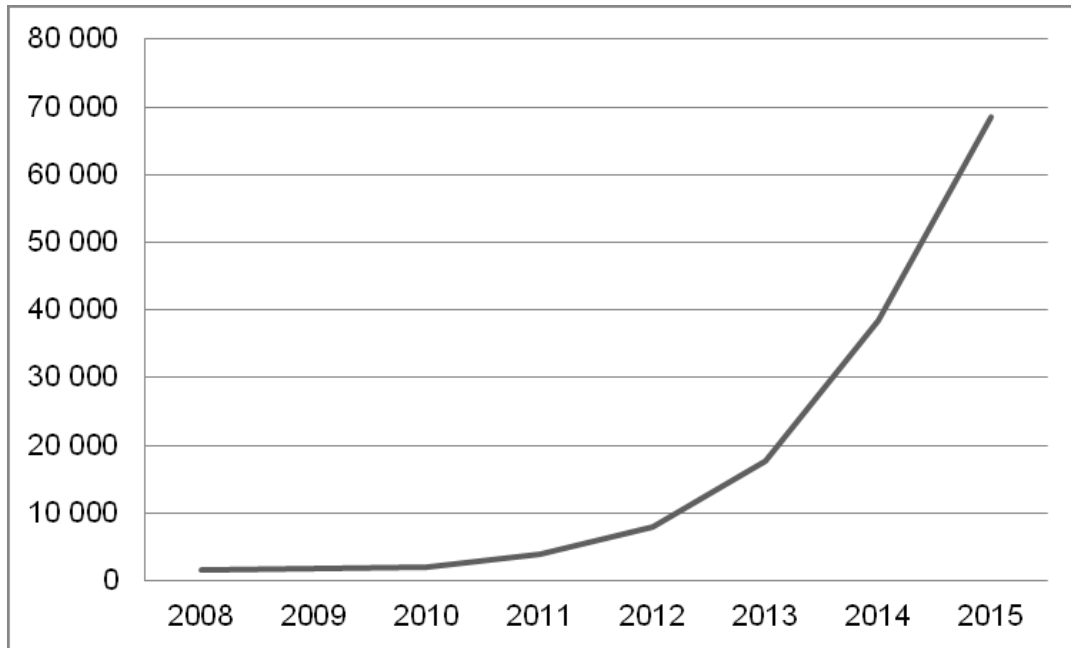


Figure 1.2. Number of registered EVs. Source: Statistics Norway.

I have made a projection of how the transformation of the car fleet can come about. The projection is made under the assumption that all cars, both EVs and gasoline- and diesel cars live for 19 years. 19 years is the average lifetime for gasoline- and diesel cars in Norway.⁶ To impose this restriction on EVs is maybe a bit hard to justify, but it simplifies the analysis. However, we know little about how long each electric vehicle actually is going to live, since most of them are rather new. And since the technology is new, it is more likely to experience breakthroughs when it comes to expected lifetime. In addition I have assumed, also for simplicity, that car sales will remain stable at 150 000 new cars each year, which was the number of new registered cars in 2015.

As mentioned above, the EV sales in 2015 accounted for 17,1 % of the total car sales. If all cars sold in Norway in 2026 shall be zero emission vehicles, the EV sales would have to increase with 8 percentage points a year. This gives the transformation displayed in Figure 1.3. The y-axis displays the total number of

⁶<https://www.motor.no/artikler/dette-er-bilene-som-gar-forst-i-vrakpressa/>

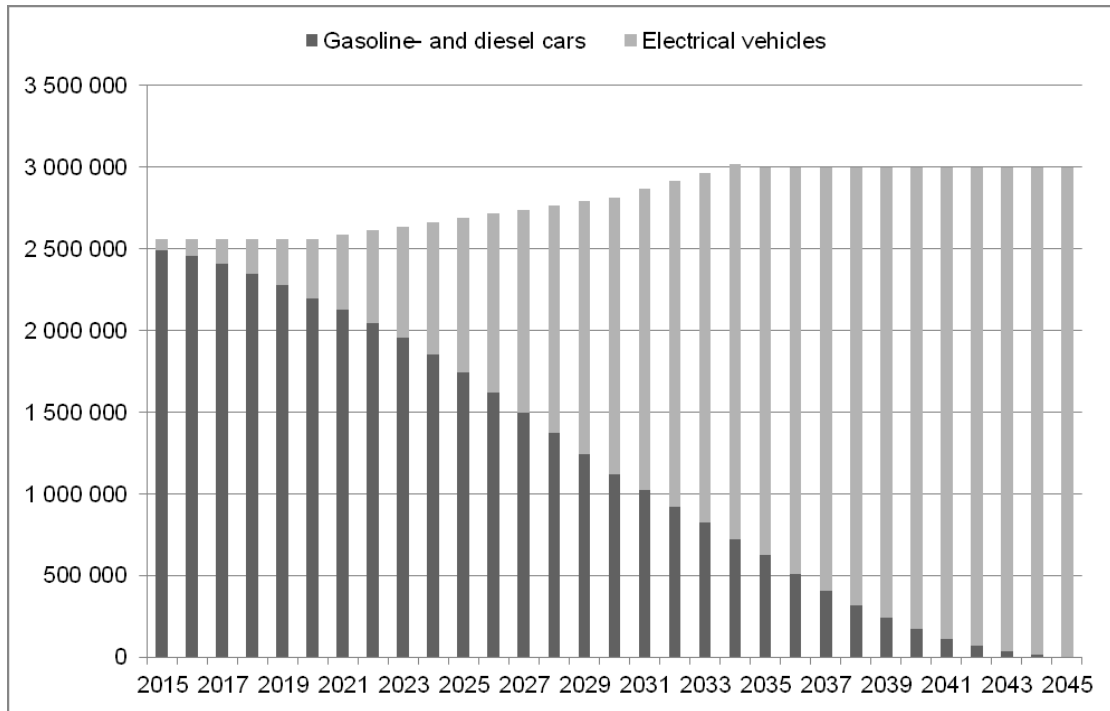


Figure 1.3. Projection of the transformation of the car fleet.

vehicles. The bar for 2015 shows the actual division between EVs and gasoline- and diesel cars, while the others are projected. Since EV sales are projected to increase with 8 percentage points each year until 2026, and gasoline- and diesel cars are conversely projected to decrease with the same amount, the last gasoline- and diesel car will then be sold in 2025, and exit the market in 2044. Due to the durability of cars, the transformation will take time. From Figure 1.3, we can see that it will be well over 1 million gasoline- and diesel cars in 2030.

Again, this is based on the assumption that the market share of EV sales must increase with 8 percentage points a year if the government is to reach their target. This is rather ambitious, bearing in mind that the market share of EV sales only increased with 4,6 percentage points in 2015. In order to obtain the much wanted transition, the quality of the EVs is essential. But nearly as essential is the quality of the charging network. It is the gasoline- and diesel car owners of today that have

to make the transition to electric vehicles in the years to come. They are accustomed to a well functioning infrastructure of petrol stations. The corresponding infrastructure of charging stations is inferior to put it mildly. However, it is being constantly improved. In this thesis I will focus on the charging market, and in particular how the structure of charging networks affects the diffusion of EVs.

1.1.1. The Current Market

More and more brands are making electric vehicles. Today the brands with models sold in Norway are: Volkswagen, Nissan, Tesla, BMW, Ford, Mercedes, Mitsubishi, Kia, Renault, Peugeot and Smart. The most popular models are: Volkswagen e-Golf and e-Up, Nissan Leaf and Tesla Model S. Most of the cars do not differ much when it comes to the specifics. They can at most drive around 200 km, but usually start to run out of power after 100 km. It depends on driving patterns, weather conditions and especially temperature. Because of the short range, most EVs are only suitable for day to day use and not for longer rides. Except for one brand, namely Tesla, which stands out as the only brand with significantly longer range. Their Model S and -X can drive between 355- and 613 km before they have to recharge.⁷ Other car manufacturers report that they have cars in production that will compete with Tesla. Opel newly stated that their Ampera-e, which is coming on the Norwegian market in 2017, will be able to last up to 500 km.⁸ In October 2016, Mercedes launched their new production line of electric vehicles called EQ, which stands for "Electric Intelligence".⁹ They reported that the first EV in this series were going to have a range of 500 km. But until all these new models are on the market, Tesla is alone when it comes to delivering long range EVs.

As already stated, in 2009 the Norwegian government started to subsidize the infrastructure of charging stations. One reason was to make it more tempting for

⁷<http://www.tu.no/artikler/her-er-rekkevidden-pa-elbilene-du-kan-kjope-na/350874>

⁸<http://www.tu.no/artikler/la-frem-bevis-pa-at-ampera-e-har-rekkevidde-pa-over-500-km/358722>

⁹<http://www.tu.no/artikler/dette-er-mercedes-kommende-elbil/358706>

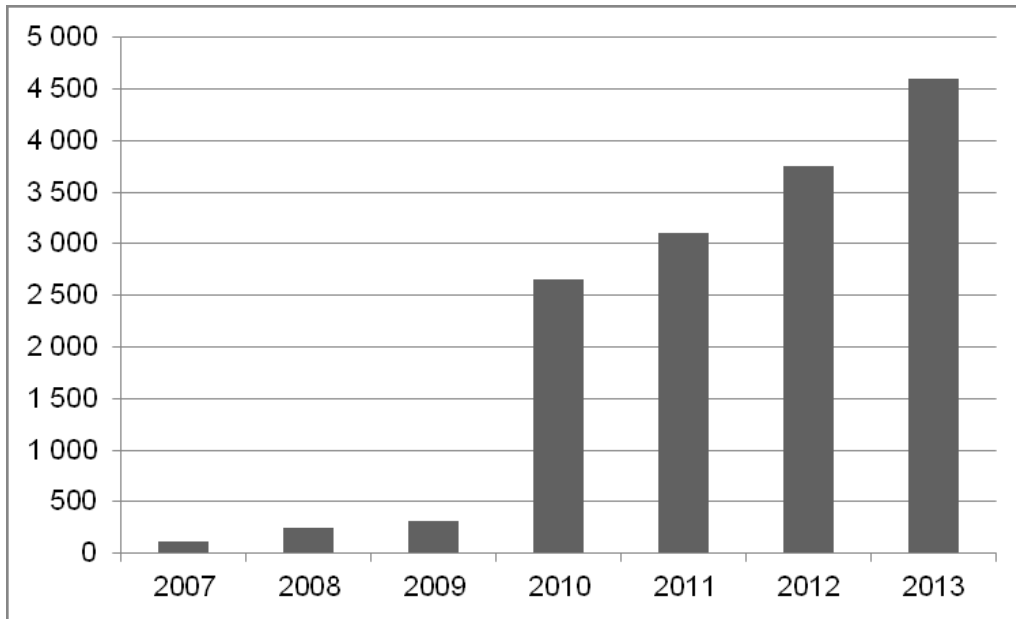


Figure 1.4. The total number of separate chargers.

consumers to get an EV. Up to that point, and even today, the most common excuse for not having an EV, is the fear of running out of power. What many refer to as: "Range anxiety".¹⁰ By now there are 1954 charging stations in Norway, with 8303 separate chargers.¹¹ In Figure 1.4, we can see the development in the number of installed chargers.¹² The public sponsorship which started in 2009 marks a significant jump in the number of installed chargers.

Charging stations have different amount of separate chargers, and different types of chargers. The different types vary in how much power per time unit they can supply the vehicles with. Of the 1954 charging stations, 415 are classified as fast- or quick charging stations.¹³ This means that they are able to charge with an effect up to 50 kilowatts.¹⁴ For short range EVs, this equals the possibility of being able to go from 0 to 80 % of full capacity in under 30 minutes. 80 % of full capacity

¹⁰https://en.wikipedia.org/wiki/Range_anxiety

¹¹<http://info.nobil.no/> updates the number of chargers daily on their frontpage. These numbers are per 04.11.2016.

¹²<http://www.ladestasjoner.no/nyheter/138-4-642-ladepunkt-for-elbiler-i-norge>

¹³<http://info.nobil.no/>

¹⁴<https://www.ladestasjoner.no/hurtiglading/om-hurtiglading/24-hva-er-hurtiglading>

amounts to around 100 km for most short range EVs. While Tesla, with a larger battery can charge up to 136 km in half an hour using the same charger.¹⁵ This is due to technology differences, and because the charging process slows down as the battery reaches its full capacity. The 1539 charging stations that are not classified as quick charging stations have chargers which support effect levels between 3,5 and 12 kilowatts, which gives approximately 100 km worth of range in the time interval of one to five hours. A charger which use up to five hours to give significant range, has presumably little or no effect on the consumers range anxiety. It is at least fair to assume that quick chargers have more of an effect, thus I will focus on the quick charging market in this thesis.

But opposed to all other EVs, Tesla has their own charging network.¹⁶ Today, it consists of 27 charging stations with a total of 212 chargers. These chargers are called: "Superchargers", and charge with an effect up to 120 kilowatts. Using a Supercharger, a Tesla can get power similar to 270 km within half an hour. Tesla is the only brand which have this technology, and batteries that are able to receive power with such great effect. How long this will be the case, remains to see. Superchargers are more than twice as fast as the quick chargers, and it might be that new quick chargers have to be built in order for new long range EVs to be attractive.

The quick chargers, except from Tesla's, are mostly publicly sponsored. They are distributed strategically all over Norway to cover the most demanded areas, as well as the most exposed distances for longer trips. This is due to how the public funding system works. The public enterprise Enova hands out financial support by announcing at which places or along which roads they want quick charging stations. Companies then apply for funds to put up charging stations at the given locations. The company that applies for the smallest amount wins the opportunity to build the station, with the respective funding they applied

¹⁵https://www.tesla.com/no_NO/supercharger?redirect=no

¹⁶https://www.tesla.com/no_NO/supercharger

for. With time several operators have entered the market: Fortum Charge & Drive, Grønn Kontakt, Tesla, Circle K, Arctic Roads, BKK and Lyse. Some more influential than others, where Fortum Charge & Drive and Grønn Kontakt have established themselves as market leaders. As of today they have 130 and 75 quick charging stations respectively. Except from Tesla, the charging suppliers are pretty equal. All EVs can charge at all the different stations, that is, they provide the different cables and sockets such that all EVs can use their chargers. The only way they differ is in the way they charge the customers. Some operate with subscribers, some charge per minute, others by units of power and so on. When it comes to Tesla's Superchargers, they can only be used by Tesla Model S or -X owners, and to them, they are free of charge.

1.2. Point of Departure

In this thesis I will divide the EV market into two segments. The first is the EV as the second family car. Second, in the sense that it does not replace the main family car used for all purposes. It is used for short hauls, and is usually charged at home. Most of the EVs we have today fall under this segment. This is supported by a survey conducted by the Norwegian Institute of Transport Economics. They have held several big surveys to learn more about EV owners, and how they utilize their cars and charging opportunities. According to the most recent one held in the spring of 2016, most EV owners have at least one additional car: "(...) the majority of BEV(battery electric vehicle) owners, (79 %) belong to multivehicle households" (Figenbaum and Kolbenstvedt, 2016). When it comes to driving patterns, the EV owners use their EVs less for trips and vacations than conventional car owners: "BEV owners use their BEVs more for all types of trips in everyday traffic but less on non-routine trips and vacation, than PHEV(Plug-in Hybrid Electric Vehicle) and ICEV(Internal Combustion Engine Vehicle) owners do" (Figenbaum and Kolbenstvedt, 2016). With respect to charging, 94-95 % report that they charge their EVs at home.

Now the second segment is the EV as the first- or only family car, which is used both for long and short hauls, and is more likely to make use of quick charging stations. Up until now, Tesla is the only EV brand which can claim to fall under this segment due to their long range. But as mentioned, several car manufacturers are developing long-range EVs. If the Norwegian government is to come anyway near their climate target, the EV has to become the first- or only family car for more households. Today, most EVs are second family cars, and 44 % of all households (1 million households) own just one car. Thus, the main focus of my thesis will be on the second segment of EVs: the EV as the first- or only family car.

The EV as the first- or only family car will make more use of charging stations alongside the roads. However, most of the stations we have today, even the ones of Tesla are inferior compared to the conventional gas stations. It takes a gasoline- or diesel car under five minutes to refill the tank, and it lasts for well over 500 km. While the quick charging stations for EVs are cheaper, it takes half an hour to get 100 km worth of range. In this respect it seems difficult, almost impossible, for long-range EVs to compete with gasoline- and diesel cars. I will thus make the assumption that new and faster charging systems would have to get in place in order for the diffusion of EVs to come about. This has been recognized by the EV manufacturers as well, as several of them supposedly have faster charging systems in the making.¹⁷ Audi, BMW and Renault are all part of a project called: Ultra E, which aims to supply Europe with an "Ultra-Fast-Charging" network. According to one of their own press releases, their system will be three times faster than the existing quick charging system.¹⁸

When I assume that new charging systems have to get in place, I here mean new charging technologies and new charging stations. In the construction of these new systems, each brand has to decide on which charging technology to be compatible

¹⁷http://www.tu.no/artikler/glem-hurtiglading-na-kommer-ultra-hurtigladerne/363399#cxrecs_s,
<http://www.tu.no/artikler/porsche-jobber-for-a-unnga-tesla-fella/358864>

¹⁸<https://www.allego.eu/wp-content/uploads/2016/10/18102016-Ultra-E-Press-Release-1.pdf>

with. What is often referred to as: the choice of compatibility. In the case of incompatibility, each EV brand is assumed to have their own charging technology with their own charging stations. Whether the EV brands have built the stations themselves or if a power company like Fortum has done it, does not really matter. The important thing is that in the case of incompatibility, each EV brand has their own charging stations.

Greaker and Heggedal (2010) have made a model where the number of filling stations for hydrogen is increasing in the market share of hydrogen cars. I will adopt this framework by assuming that the number of charging stations is increasing in the number of EVs. Specifically, a given number of EVs corresponds to a given number of charging stations. This will matter for the consumers as they are assumed to derive higher utility from an EV, the more charging stations they can use.

Now, the EV manufacturers can also choose to be compatible to other charging systems. Say two brands choose to be compatible to the same charging technology. Then the consumers of both brands share each others charging stations. The consumers will then be able to charge at more stations, and consequently derive higher utility from their EVs. This will in turn affect the sales of the two brands because the consumers will have higher willingness to pay for their EVs.

Thus, in the next chapters I will analyze how the choice of compatibility with respect to charging technology affects the diffusion of EVs. Not surprisingly, complete compatibility leads to greater diffusion of EVs than incomplete compatibility. In other words, if all electric vehicles can use all charging stations, more people will buy electric vehicles. This will seem to maximize social welfare, but may very well not be the realized market solution. To address this matter I will compare the private and social incentives for achieving compatibility. The analysis is based on a formal model of network competition introduced in Katz and Shapiro (1985). I will do some modifications to their model, and apply it to the EV- and charging market.

1.3. Related Literature

Katz and Shapiro (1985) is just one paper in what has become a literature of network externalities. Network externalities are basically positive consumption externalities, where one more consumer unintentionally increase the utility of all other agents consuming the same good. A frequent used example is the telephone, where the utility a consumer derives clearly depends upon the number of users who have joined the telephone network (Rohlfs, 1974). They can either be direct, where communication services like the telephone or Facebook are good examples. Or indirect, where more consumers joining the "network" increase the quality and variety of complimentary products supplied. Examples could be that more programs are written for a popular computer, or that more car dealers provide service for a popular automobile (Tirole, 1988).

The EV is associated with several network externalities. Most of them are indirect, but it has been stated that EVs one day might be able to use their batteries for other purposes than driving.¹⁹ Then one could argue that the EV is associated with direct network externalities, because the EVs could potentially charge each other. However, the indirect effects of better complimentary products and more charging possibilities are more natural to think of. And it is in particular this latter effect of more charging possibilities I will study in this thesis.

In the literature of network externalities the concepts of compatibility and standardization is widely discussed. There are often benefits for both consumers and firms from a standardization of a product. However, these benefits can possibly "trap" an industry to choose- or stick with an inferior standard, which leads to excess inertia (Farrell and Saloner, 1985). Excess inertia occur for example when an industry choose to stick with an old technology, even though a new one clearly yields higher welfare. A commonly used example is the story of the QWERTY keyboard, where the users got locked in. Alternatives such as the Dvorak keyboard has been claimed to be more efficient, but could never compete as the QWERTY

¹⁹<https://www.nrk.no/ostfold/elbilen-din-kan-bli-brukt-til-lagring-av-vindkraft-1.13082941>

was adopted as the standard (David, 1985). In the case of EVs and gasoline- and diesel cars, the transformation to EVs could be too slow because the EVs suffer from excess inertia, as discussed in Greker and Midttømme (2016).

Katz and Shapiro (1986a) analyze network externalities and standardization in a dynamic framework with two firms that live for two periods. There are different consumers in both periods. The consumers of the second period are assumed to derive positive network effects if their product was widely used in the first period. The firms incorporate this effect and may use approaches such as penetration pricing in order to become the standard chosen by consumers in both periods. This could be what Tesla is trying to do now, by handing there consumers a superior charging network free of charge in order to get a built-in advantage they can benefit from in the future.

However, out of this literature, it is only Katz and Shapiro (1985) which analyze the choice of compatibility in a competitive setting suited for the EV- and charging market. Therefore most of the analysis is based on this paper.

One of the key assumptions I make in this thesis, is how the consumers' willingness to pay rely on the size of the charging network. So far I have just stated that their utility is assumed to be positively correlated with the number of charging stations. Later on I will assume a strong relationship between the size of the charging network and the willingness to pay for an EV. This is supported by Sierzchula et al. (2014) and Zhang et al. (2016).

Sierzchula et al. (2014) conduct a multiple regressions analysis with data on EV market shares, charging infrastructure and several socio-economic factors from 30 countries. Using ordinary least squares they find that charging infrastructure has a positive and statistically significant effect on a country's market share of EVs. In particular they find that: "(...) each charging station (per 100.000 residents) could have twice the impact on a country's EV market share than 1000 \$ in consumer financial incentives" (Sierzchula et al., 2014).

Zhang et al. (2016) use a Random-Coefficient Discrete Choice model with Norwegian data on EV sales and demographics to understand the choices of electric vehicle consumers and -business buyers. They include several characteristics of the vehicle and especially three policy incentives: bus lanes access, toll waiver and charging stations. Regarding the incentives they find that the amount of charging points has the strongest effect among both personal consumers and business buyers:

“Among the three incentives, we find that the number of charging points has the greatest and most significant interaction coefficients. (...) This positive effect seems to indicate establishing charging infrastructure is the most efficient way for BEV adoption among the three incentives. The denser charging station networks a municipality has, the more BEVs are likely to be sold” (Zhang et al., 2016).

The rest of the thesis is organized in the following way: In the next chapter I present the model, before I characterize the different equilibria in Chapter 3. I analyze the private- and social incentives for achieving compatibility in chapter 4. Chapter 5 includes an extension of the model where I solve for an asymmetric equilibrium. While Chapter 6 includes a brief summary of my results, a discussion and some concluding remarks.

CHAPTER 2

Model

Katz and Shapiro (1985) introduce a static, one-period, partial equilibrium model. Even though the EV market is not static, I still think it is possible to use the model to look at the EV market if we regard the single period to be many years. The model is similar to a standard Cournot game, where each manufacturer maximizes its profits given the quantity chosen by the others. But in addition, each EV manufacturer has to choose which charging system to be compatible with. The decision will affect the size of their associated charging network, which in turn will determine the consumers' demand, and ultimately their sales. However, the choice of compatibility is often associated with high costs. If the choice is to be incompatible to all other charging networks, one has to bear the costs of building own charging stations. If it is to be compatible with another charging network, one might face costs related to developing and designing a standard. Hence, which charging system to be compatible with is an important decision, one that is often meant to last. Therefore the periods are assumed to be long, say ten years. So ahead of a ten-year period, the consumers form expectations about how the EV- and charging market will look like before making their purchasing decision. While each EV manufacturer maximizes its profits given the expectations of the consumers, and the quantity chosen by the other manufacturers. In my analysis I will only consider a representative ten-year period, and look at how different compatibility decisions lead to different realizations of output, i.e. different numbers of produced EVs. Given Norway's climate targets, it is natural to think of the representative period as the ten-year period between 2020 and 2030.

2.1. Consumers

There are M consumers. All of them buy one car, but contingent on the consumer surplus, it will either be an EV or a gasoline- or diesel car. A gasoline- or diesel car is in this model categorized as the "fall back" car. If the utility derived from an EV is not high enough, one will always buy a gasoline- or diesel car. Formally, the utility a consumer derives from a gasoline- or diesel car is normalized to zero. Hence the only consumer surplus I will derive is with respect to an EV. If it is non-negative, the consumer will buy an EV, while if it is negative he or she will buy a gasoline- or diesel car and receive 0. The consumer surplus of an EV is thus always compared to the normalized utility level of a gasoline- or diesel car.

As described above, the utility a consumer derives from an EV depends upon the size of the associated charging network. Since it is a one-stage game, the consumers cannot observe the different network sizes before making their purchasing decision. Hence, they make their decision based on expected network sizes. Very similar to what actually is the case in the EV- and charging market today. As mentioned in the Introduction, the long-range EVs like Opel Ampera-e and Mercedes EQ are about to enter the market.¹ However, this will be before a new and appropriate charging system is in place. The Ampera-e will be able to charge at the existing charging stations, but new and faster charging systems are likely to get in place during its lifetime.² Thus, the consumers have to make their purchasing decision based on expected charging network sizes.

The timing is as follows. First the consumers form expectations about the network size of each manufacturer, essentially, how many consumers will be able to use the same charging system or -systems. Second, the EV manufacturers play an output game, where consumers expectations are taken as given. This game, a standard Cournot game where the manufacturers choose their produced

¹First paragraph, Section 1.1.1. The Current Market.

²<http://www.tu.no/artikler/derfor-kan-du-ikke-lade-elbilen-raskere/277446>

quantity simultaneously, generates a set of prices. Consumers then make their purchasing decision by comparing the actual prices, with their reservation prices based on their expected network sizes. This process is not formally modeled, but to simplify, only fulfilled expectation equilibriums are to be characterized in this analysis. That is, the consumers expectations are always fulfilled in equilibrium. Hence, the generating process of expectations is irrelevant.

Let n denote the number of EV manufacturers or -brands in the EV market. x_i^e denotes the number of EVs a brand i is expected to sell. Since each consumer only buys one car, this equals the amount of consumers brand i is expected to have. Each brand is associated with a charging network. The size of the network is made up by the amount of consumers who can use the same charging stations. Let y_i^e be the expected network size of brand i . As discussed in the Introduction,³ a given size of the charging network correspond to a given number of charging stations. And in particular, the bigger the charging network is, the more charging stations it consist of.

In the case of complete incompatibility, where the consumers only can use the charging stations of its associated brand, each brand's expected sales makes up their expected charging network: $y_i^e = x_i^e$. In other words, the amount of consumers that can use the charging network of brand i is the amount of consumers that own an EV from brand i . However, when EVs from different brands can use the same charging stations, that is when EV brands are compatible with the same charging stations, then the size of a brand's charging network exceeds their sales: $y_i^e > x_i^e$. Say brands 1 and 2 can use the same charging stations, then both brand 1 and 2 have an expected network size of $y_1^e = y_2^e = x_1^e + x_2^e$. More formally, we have that when brands 1 through k are compatible with the same charging stations, the sales of these k brands make up the size of the charging network:

$$y_i^e = \sum_{j=1}^k x_j^e \text{ for } i = 1, 2, \dots, k.$$

³Fourth paragraf, Section 1.2. Point of Departure.

A brand i has an associated charging network to the sales of all k brands, because all the k brands share the same charging stations. This holds true for all the k brands.

Networks are assumed to be homogeneous in the sense that two networks of equal size are viewed as perfect substitutes. In other words: The charging systems are assumed to be equally good when the number of users are the same. This could for example relate to charging quality, charging time and how widespread the charging stations are.

Following Katz and Shapiro (1985), consumers are assumed to be heterogeneous in their basic willingness to pay, but homogeneous in their valuations of the charging network. In particular, the willingness to pay for a consumer of type r is defined as: $r + v(y^e)$. Where r denotes the basic willingness to pay, i.e. the willingness to pay for an EV if there were no charging system, and $v(y^e)$ measures the value he or she attaches to the associated charging network. The basic willingness to pay is heterogeneous in the sense that it varies across consumers, in particular it is assumed to be uniformly distributed between minus infinity and A , where A is assumed to be positive. The valuation of the network is equal for all consumers, hence it is homogeneous. Specifically $v(y)$ is twice continuously differentiable with $v' > 0$, $v'' < 0$, $v(0) = 0$, and $\lim v'(y) = 0$ as $y \rightarrow \infty$. This gives that each new member of the charging network increase the consumers' willingness to pay, but on the margin each new member contributes less than the previous one.

Each agent purchases the brand that maximizes his or her surplus given by:

$$r + v(y_i^e) - p_i, \tag{2.1}$$

where p_i denotes the price for an EV of brand i . In other words a consumer of type r chooses the EV for which (2.1) is largest. If the agent has negative surplus for all n EV-brands, he or she chooses a gasoline- or diesel car and receives 0 by assumption.

2.2. Firms

Since the EVs are assumed to be homogeneous, two firms i and j will both have positive sales if and only if the price adjusted for network size is equal for both firms:

$$p_i - v(y_i^e) = p_j - v(y_j^e) \quad (2.2)$$

If for example firm i were to have a smaller charging network, but equal price as firm j , then no consumers would buy an EV of firm i because the EV of firm j would clearly lead to higher surplus, and vice versa. Let ϕ denote the common value of (2.2), also referred to as the expected hedonic price. Hedonic prices takes into account external factors which affects the utility derived from the good. In this case the consumers earns the benefit of a charging network, hence the expected hedonic price equals the price adjusted for the network size: $\phi = p_i - v(y_i^e)$.

Again, only those consumers who derives non-negative surplus from an EV will buy an EV:

$$r + v(y_i^e) - p_i \geq 0,$$

inserting for the expected hedonic price ϕ yields:

$$r \geq \phi$$

Thus, only those consumers with a basic willingness to pay larger than or equal to the expected hedonic price will enter the EV-market. Given the uniform distribution of the basic willingness to pay: $r \sim U(-\infty, A)$, $A - \phi$ consumers will enter the EV-market. Where the type with $r = \phi$, by assumption is indifferent between an EV and a gasoline- or diesel car. The number of consumers entering the EV market, $A - \phi$, makes up the demand for EVs. The supply is given by the total sales of the EV industry z , defined as: $z \equiv \sum_{i=1}^n x_i$. In equilibrium prices must be

set such that demand equals supply:

$$\begin{aligned} A - \phi &= z \\ A + v(y_i^e) - p_i &= z \end{aligned} \tag{2.3}$$

From this we can derive the price which each firm i will receive in equilibrium:

$$p_i = A + v(y_i^e) - \sum_{i=1}^n x_i, \tag{2.4}$$

in other words, the demand function for an EV of brand i . It is fairly similar to an ordinary downward sloping demand curve, where the demand increases as the price falls. What makes it differ, is that increased sales will increase the network size, and hence the consumers willingness to pay.

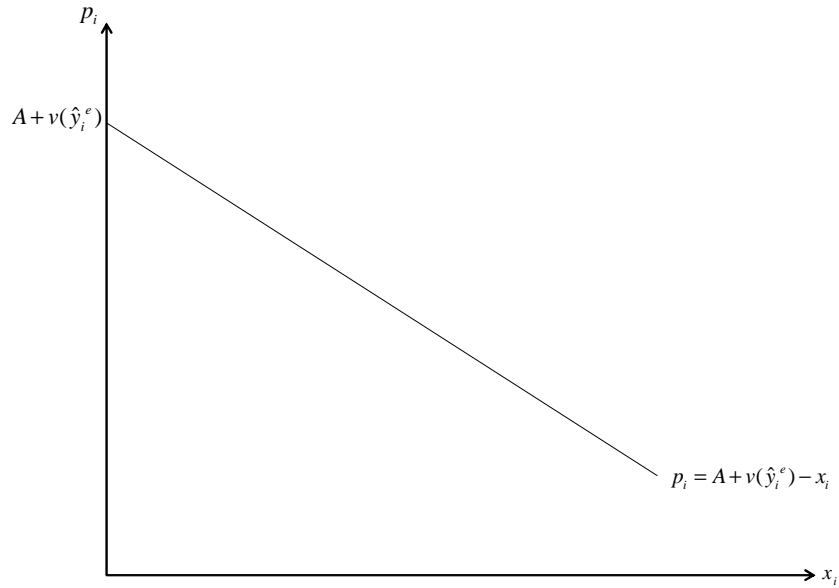


Figure 2.1. Demand curve for an EV of brand i , with a given network size \hat{y}_i^e .

With a given network size \hat{y}_i^e , the demand function of brand i is a standard downward sloping demand curve. It is displayed in Figure 2.1 with price on the y-axis and quantity on the x-axis. $A + v(\hat{y}_i^e)$ is the constant term, and the slope coefficient equals: -1 .

2.2.1. Costs

There are two types of costs that need to be taken into account. First, there are costs of production. They are assumed to be the same for all firms, and take the form of a fixed cost G , plus a constant per unit cost c . The fixed cost can be thought of as sunk cost, for example related to R&D. While the per unit cost could be the material- and labor cost needed to produce an EV. The associated costs of putting up charging stations are assumed to enter in the constant per unit cost. The production cost of firm i producing x -units can be summarized to: $G + cx$.

In principle, there is free entry into the vehicle market, but since the EV technology is rather new, substantial investments have to be made in R&D in order to become an EV manufacturer. To fix the number of EV manufacturers to n , I will assume that G is high enough such that no potential entrants have an incentive to enter. For simplicity however, G is assumed to be lower than net equilibrium profits, such that the equilibrium output is unaffected by the fixed costs.

While the EV technology is rather new, the gasoline- and diesel car technology is old. Thus, the potential gasoline- and diesel car manufacturers do not encounter a development cost, such as the EV manufacturers. In this sense, the barriers for entering the gasoline- and diesel car market are lower, which leads to higher competition. In particular, I will assume that there is perfect competition in the gasoline- and diesel car market, i.e. cars will be sold at prices equal to marginal costs. Since the consumers are assumed to derive zero benefits from a gasoline- or diesel car, they will be traded at prices equal to 0.

Today the marginal costs of producing an EV are higher than that of a gasoline- or diesel car. But this is likely to even out as the cost advantages in the gasoline- and diesel car industry are mostly due to economies of scale (Norwegian Environment Agency, 2016). Most EVs are being built on production lines suited for ordinary gasoline- and diesel cars, and not EVs. But as the sales have started to take off, the EV manufacturers have begun to rig their factories for mass production.⁴ In addition, the production costs of batteries have declined rapidly over the last couple of years, and are predicted to continue to do so (Norwegian Environment Agency, 2016). Thus, since I am looking at the period 2020-2030 I will assume that the cost levels evens out. In particular I will assume that the marginal cost of an EV equals the marginal cost of a gasoline- or diesel car, namely zero. Assuming $c = 0$, is equivalent to redefining r . r is defined as the a consumer's basic willingness to pay. Now it can be interpreted as a consumer's basic willingness to pay over the marginal cost. It is for this reason negative values of r makes sense. A negative r now means that the basic willingness to pay is below the marginal costs of production. However, the "total" willingness to pay might still be positive, if the benefits from the associated charging network are high enough.

The second type of cost that needs to be modeled is the cost of achieving compatibility. The EV-manufacturers have the choice to make their EVs compatible or incompatible with the existing charging systems. Like with every other decision they make, they will make the one that maximizes their profits. The cost of compatibility could for example be the costs of developing and designing a compatible charger, the costs of negotiating a standard, or the costs of introducing a new compatible charging system. These costs are also likely to be in the form of a one-time sunk cost, hence it is fair to assume that they are fixed and independent of scale. Since the compatibility costs are fixed, both the EVs that are compatible with other charging systems, and those which are incompatible, have the same marginal cost, given by the variable unit cost equal to zero. Let F_i denote the

⁴<http://www.tu.no/artikler/dette-er-mercedes-kommende-elbil/358706>

fixed costs of compatibility incurred by firm i . As noted, it may not be the same for all firms.

The gross profit of a firm i is given by:

$$\begin{aligned}\pi_i &= p_i(x_i)x_i \\ \pi_i &= x_i(A - \sum_{i=1}^n x_i + v(y_i^e)),\end{aligned}$$

from which the fixed cost of compatibility: F_i , must be subtracted to get net profits:

$$\pi_i = x_i(A - \sum_{i=1}^n x_i + v(y_i^e)) - F_i$$

In the case of complete incompatibility, where each brand only can use its own charging stations, the profits is given by:

$$\pi_i = x_i(A - \sum_{i=1}^n x_i + v(x_i^e)),$$

because each firm's associated network is made up by their sales: $y_i^e = x_i^e$. This could be thought of as a situation where all manufacturers did like Tesla, namely put up their own charging stations, only compatible to their own vehicles.

When all n charging systems are compatible, each firm is associated to the same network made up by the total sales of the industry: z . In this case, each firm has to pay the fixed cost of achieving compatibility: F_i . This gives that brand i has the following profit function:

$$\pi_i = x_i(A - \sum_{i=1}^n x_i + v(z^e)) - F_i \tag{2.5}$$

CHAPTER 3

The Characterization of Equilibria

The equilibrium concept is that of fulfilled expectations Cournot equilibrium (FECE). In equilibrium, the charging network sizes will equal the consumers expected charging network sizes, which ultimately gives that the expected sales equals actual sales in equilibrium. The firms choose their quantity simultaneously under the assumptions that: (a) consumer's expectations regarding network sizes $(y_1^e, y_2^e, \dots, y_n^e)$ are given; and (b) the actual output level of the other firms $\sum_{j \neq i} x_j = x_{-i}$ is fixed. In order to derive the equilibrium output level I solve the firms' maximization problem:

$$\begin{aligned} \max_{x_i} \pi_i &= p_i(x_i)x_i \\ &= x_i(A - \sum_{i=1}^n x_i + v(y_i^e)), \end{aligned}$$

where the first order condition is given by:

$$(A - \sum_{i=1}^n x_i + v(y_i^e)) + x_i(-1) = 0,$$

which implies that the equilibrium sales levels $(x_1^*, x_2^*, \dots, x_n^*)$ must satisfy:

$$x_i^* = A + v(y_i^e) - \sum_{j=1}^n x_j^* \text{ for } i = 1, 2, \dots, n. \quad (3.1)$$

The equilibrium sales level x_i^* depends upon the expected charging network size y_i^e and the total output of the industry, which is here denoted as the sum of the equilibrium output level x_j^* of all n brands. Note that the right hand side of equation (3.1) equals $p_i(x_i^*)$, which gives $\pi_i^* = p_i(x_i^*)x_i^* = (x_i^*)^2$.

Equation (3.1) can be solved simultaneously for the x_i^* 's to obtain the unique Cournot equilibrium:¹

$$x_i^* = \frac{A + nv(y_i^e) - \sum_{j \neq i} v(y_j^e)}{n + 1} \text{ for } i = 1, 2, \dots, n. \quad (3.2)$$

I will now characterize the different equilibria with different degrees of compatibility. First with full compatibility and then with complete incompatibility.

3.1. Complete Compatibility

Suppose all EV brands in the market are compatible with all charging stations. In other words, there exist one universal charging technology which all EVs and charging stations support. Then there is a single charging network with size equal to the expected total sales: $y^e = z^e = \sum_{i=1}^n x_i^e$. Inserting this in the unique Cournot equilibrium (3.2) gives:

$$\begin{aligned} x_i^* &= \frac{A + nv(z^e) - \sum_{j \neq i} v(z^e)}{n + 1} \\ x_i^* &= \frac{A + nv(z^e) - (n - 1)v(z^e)}{n + 1} \\ x_i^* &= \frac{A + v(z^e)}{n + 1}, \end{aligned} \quad (3.3)$$

where x_i^* denotes the individual equilibrium output under complete compatibility. It is equal for all i since all firms are associated with the same network. The equilibrium is therefore symmetric. Remember that the EVs are assumed to be homogeneous, and that they are produced at the same marginal cost equal to zero. The only thing that makes them differ is the network sizes, because the consumers assign different values to different network sizes. In the case of complete compatibility, all EVs belong to the same network. Then, when firms are to decide how much to produce, they face the same maximization problem because they maximize with respect to the same network size. Which in turn leads to the same optimal output level.

¹The calculations are done for $n = 3$ in the Appendix.

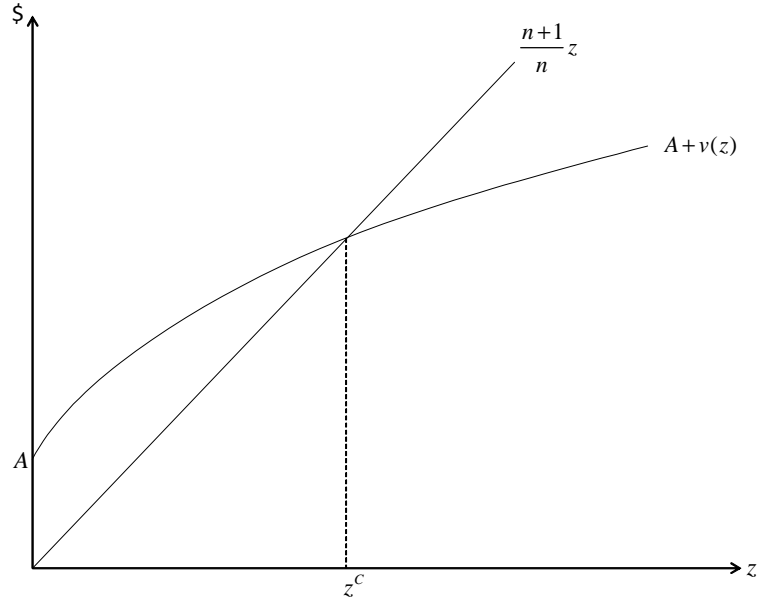


Figure 3.1. Equilibrium with complete compatibility.

Imposing fulfilled expectations implies that total expected sales will equal actual sales: $z^e = z = x_1^* + x_2^* + \dots + x_n^*$. Now summing equation (3.3) over all i gives total sales in the case of complete compatibility:

$$z^c = \frac{n}{n+1}(A + v(z^c)), \quad (3.4)$$

where z^c denotes total output in the case of complete compatibility. Equation (3.4) has a unique solution which is shown graphically in Figure 3.1. Rearranging equation (3.4) yields:

$$\frac{n+1}{n}z^c = A + v(z^c)$$

The left hand side is an increasing function with a slope of $\frac{n+1}{n}$. While the right hand side consist of a constant A , which makes up the intercept, and $v(z)$, which is an increasing function, but decreasing at the margin. The graphic solution

is depicted in Figure 3.1, with total industry output on the x-axis, and consumer surplus measured in dollars on the y-axis.

Proposition 1. *When all EVs are compatible with all charging stations, there is a unique FECE, where the total number of EVs is given implicitly by equation (3.4).*

We see that more manufacturers n , will shift the constant function $\frac{n+1}{n}z$ down to the right, leading to higher industry output. In fact, from equation (3.4) we see that z^C approaches $A + v(z)$ when n increases. Inserting this in the equilibrium price gives: $p_i = A + v(y_i^e) - z = A + v(z) - (A + v(z)) = 0$. In words: The price approaches the marginal cost level of zero, when the number of manufacturers n increase. The compatibility equilibrium hence converges to the perfect competitive equilibrium with prices equal to marginal costs, as n increases. We can also see that the closer we get to the competitive equilibrium, the higher is the realized number of EVs.

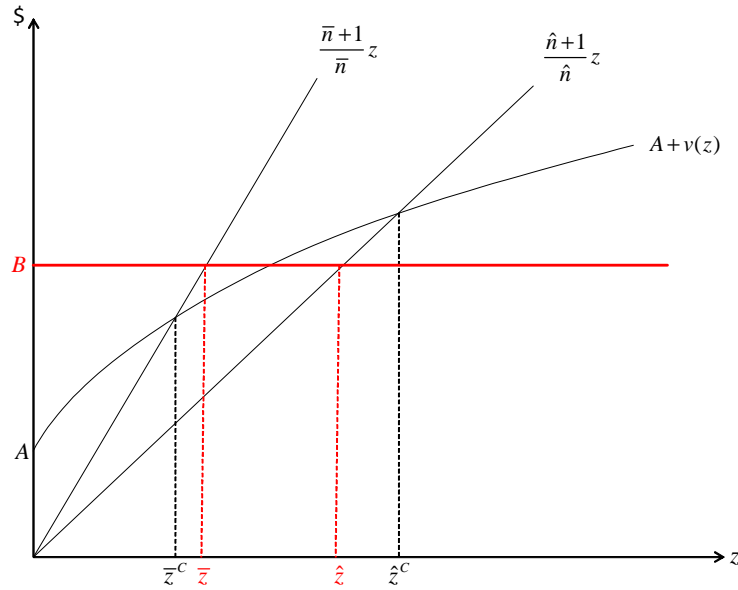


Figure 3.2. The effect of becoming more manufacturers.

Compared to a standard Cournot equilibrium without network effects, the change of one more manufacturer is bigger with network effects. This follows from the fact that increased sales leads to lower prices, which again increase consumer surplus. In Figure 3.2 the thick horizontal line indicates a standard Cournot case where there is no network effect. We can think of a case where the charging network is set, and hence does not depend on the number of consumers. B indicates the constant consumer surplus in this case. From this, we can see that the effect of increasing the industry with one more manufacturer has a larger effect when the consumers enjoy benefits from the network. Increasing the number of firms from \bar{n} to \hat{n} gives a bigger increase in the number of EVs if the consumers enjoy network effects.

3.2. Complete Incompatibility

With complete incompatibility the expected charging network size equals the expected individual sales: $y_i^e = x_i^e$. As before each firm i maximizes their profits given the quantity chosen by the other manufacturers x_j , $j \neq i$, and consumers' expectations x_i^e . Using the individual equilibrium sales level from equation (3.1), together with the assumption that expectations are fulfilled $x_i^e = x_i$, gives:

$$\begin{aligned} x_i &= A + v(y_i^e) - z \\ x_i &= A + v(x_i) - x_i - \sum_{j \neq i} x_j \\ \sum_{j \neq i} x_j &= A + v(x_i) - 2x_i, \end{aligned} \tag{3.5}$$

where $\sum_{j \neq i} x_j$ can be denoted as x_{-i} . We need to know x_{-i} , to be able to solve for the output level of firm i . In the case of complete incompatibility, several outcomes may be supported as equilibria. Since I use the equilibrium concept of fulfilled expectations Cournot equilibrium (FECE), many asymmetric equilibria can be sustained on the basis of consumer expectations. A firm can have a large market share simply because it is expected to by the consumers. This makes asymmetric

equilibria hard to characterize in general. Hence, for simplicity, I will only consider the equilibrium in the form of a symmetric oligopoly. However, in Chapter 5, I change some of the characteristics of the model in order to solve for an explicit asymmetric equilibrium.

3.2.1. Symmetric Oligopoly

With full incompatibility the equilibrium could be in the form of a symmetric oligopoly, where each manufacturer produce the same number of EVs and hence are associated to the same charging network size. As noted above it depends on the consumers expectations regarding network sizes. If the firms are expected to have equal sales, and hence equal network sizes, this could be supported as an equilibrium. To see this, one can insert $\frac{z}{n}$ for both x_j and x_i in equation (3.5):

$$\begin{aligned} \sum_{j \neq i} x_j &= A + v(x_i) - 2x_i \\ (n-1)\frac{z}{n} &= A + v\left(\frac{z}{n}\right) - 2\frac{z}{n} \\ \frac{n+1}{n}z^I &= A + v\left(\frac{z^I}{n}\right), \end{aligned} \tag{3.6}$$

where z^I denotes the industry output under complete incompatibility. As with the symmetric equilibrium with complete compatibility, the symmetric oligopoly equilibrium has a unique graphical solution. It is displayed in Figure 3.3, where the right hand side of equation (3.6) gives the consumer surplus, and the left hand side is a constant increasing function.

As we can see from Figure 3.3, the consumer surplus increase with total output, but decrease at the margin due to the properties of the network value function. The unique industry output level: z^I , is given by where the two functions intersect.

Proposition 2. *When each EV brand is only compatible with its own charging system, there exist a unique symmetric equilibrium in which all manufacturers produce $x_i = z^I/n$.*

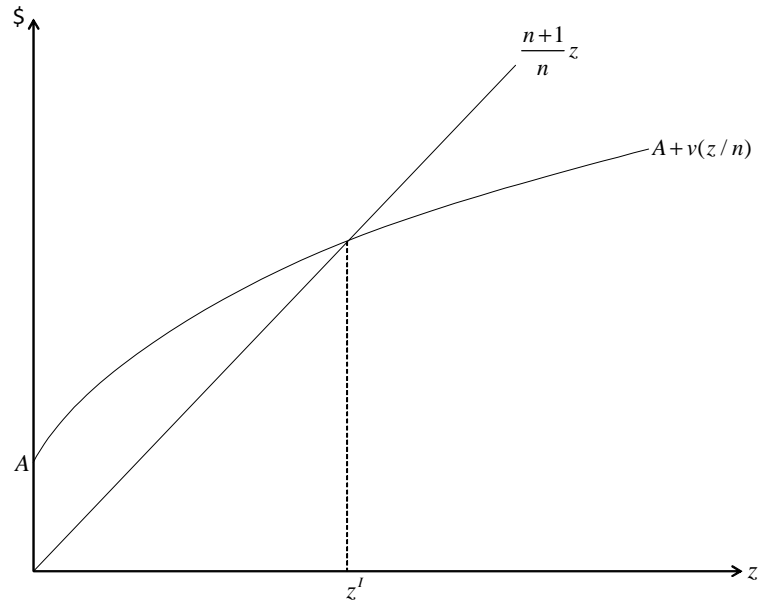


Figure 3.3. Symmetric oligopoly equilibrium.

3.3. The Output Effects of Compatibility Choices

Remember that all EV manufacturers with a positive level of output will have sales equal to:

$$x_i = A + v(y_i^e) - z$$

By summing the individual sales of all n firms, we can solve for the industry-wide output z :

$$\begin{aligned} \sum_{i=1}^n x_i &= nA + \sum_{i=1}^n v(y_i^e) - nz \\ z &= nA + \sum_{i=1}^n v(y_i^e) - nz \\ (n+1)z &= nA + \sum_{i=1}^n v(y_i^e) \end{aligned}$$

Since A and n are fixed parameters, the total number of EVs only depend upon the expected charging network size y_i^e , i.e. how many consumers use the charging stations associated with brand i .

3.3.1. Complete Compatibility Versus Incomplete Compatibility

When all EVs are compatible with all charging stations, there is one network, and it consists of all EV consumers: $y_i = z$. Hence all consumer are subjected to the same charging network, which gives them the same utility from the network. While if an EV brand i is incompatible with the charging stations of other brands, their network is smaller than what it could have been, had it been compatible with all others: $y_i < z$. Therefore, one can characterize the industry-wide output in the case of complete- and incomplete compatibility. In other words, where all EVs can use all chargers, and where at least one brand is incompatible with the charging systems of the others. In the former case, all n consumers face the same network and derive the same network value. However, in the latter case, all n consumers face smaller networks: $y_i < z$, giving them less network value than in the case of complete compatibility.

The industry-wide output under complete compatibility is characterized by:

$$z = \frac{nA + nv(z)}{n + 1}$$

While for incomplete compatibility by:

$$z = \frac{nA + \sum v(y_i)}{n + 1}$$

Since v is an increasing function we have that: $v(z) > v(y_i)$, when $z > y_i$. This also gives: $\sum v(z) = nv(z) > \sum v(y_i)$. Thus, the amount of EVs are greater when all EVs can use all types of chargers than in any other equilibrium where this is not the case. This is shown graphically in Figure 3.4. The function $nA + nv(z)$ will always lie above $nA + \sum v(y_i)$, and hence the number of EVs under complete compatibility will always be greater than under incomplete compatibility. This is due to the fact

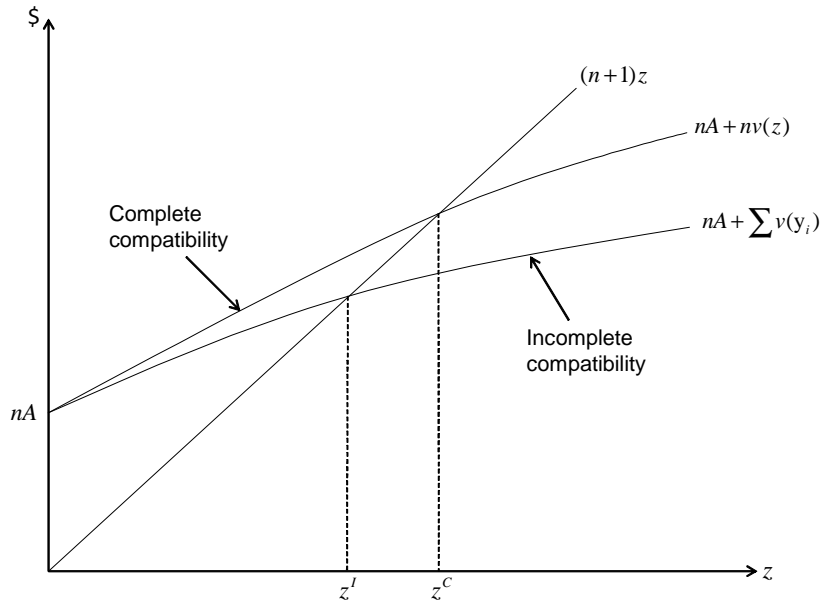


Figure 3.4. Complete versus incomplete compatibility

that the consumers derive higher utility the bigger the charging network is. The charging network is as big as it can possibly be with full compatibility, but when at least one brand becomes incompatible to the others, the charging network for all consumers becomes smaller. The consumers then derive less utility from their network, and less consumers will enter the EV market because they derive higher utility from a gasoline- or diesel car.

Proposition 3. *The amount of EVs is greater with complete compatibility between EVs and charging systems, than in any equilibrium with incomplete compatibility.*

3.3.2. Different Degrees of Compatibility

Could it be that a higher degree of compatibility always leads to more EVs? I have mostly discussed either complete compatibility or complete incompatibility, but there are many different degrees of compatibility in between these two extremes.

To address this matter, we can think of a case where two brands merge, in the sense that they make their charging stations compatible to each other's EVs. If this increases the total number of EVs, a higher degree of compatibility will always lead to more EVs.

Say brands 1 and 2 merge. Without the merger, they will produce according to their own network size y_i :

$$x_i = A + v(y_i) - z \text{ for } i = 1, 2.$$

but after a merger they will face a larger network, namely equal to the pre-merger network size of both firms:

$$x_i = A + v(y_1 + y_2) - z \text{ for } i = 1, 2. \quad (3.7)$$

One would believe that a bigger charging network increase the merging firms' production, but this all depends on the response from the non-merging firms, as the production level depends upon the industry-wide output: z . Remember that the output decision of all firms, merging and non-merging, depends upon the level of industry output: z . Thus, if the merger increase the production level of the merging firms, it change the equilibrium output decision of all the non-merging firms. We can look at this by graphing how a non-merging firm j will react to changes in the total output. This is shown in Figure 3.5. As long as: $A - z \geq 0$, the graph of x_j and $A - z + v(x_j)$ will intersect and the output of a non-merging brand: x_j , will be defined. The total number of EVs z , is treated exogenously and hence enter in the constant term. If total output changes as a result of the merger, the graph will shift in the diagram and change the equilibrium output decision x_j . An increase in the total number of EVs z , will shift $A - z + v(x_j)$ down, leading to fewer units sold for a non-merging brand j . This case is depicted in Figure 3.5, where \bar{z} and \hat{z} denotes pre- and post-merger industry output respectively. If the merger causes industry output to increase from \bar{z} to \hat{z} , it will reduce the equilibrium output level of a non-merging firm from \bar{x}_j to \hat{x}_j .

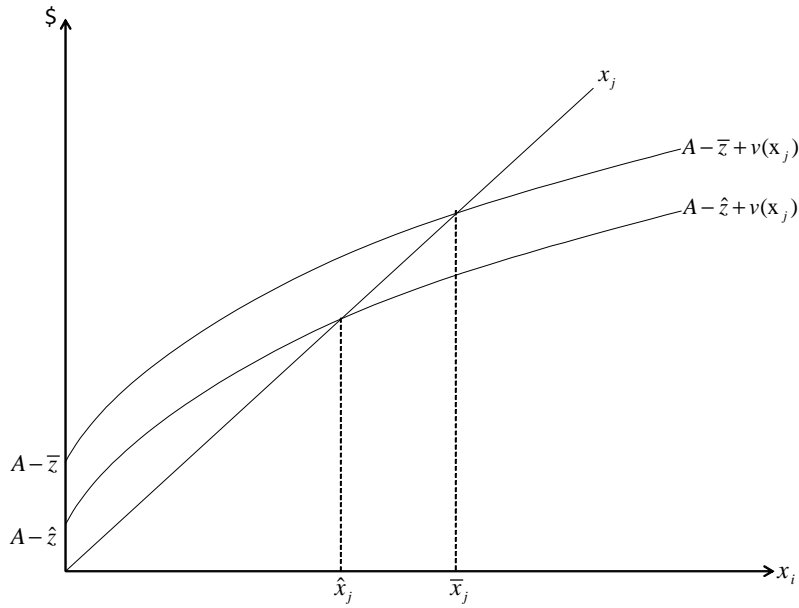


Figure 3.5. Output response from a non-merging manufacturer to a change in industry output.

However, the opposite holds true if we reverse the argument: If the merger causes industry output z , to decrease, it will shift $A - z + v(x_j)$ up, which gives that a non-merging firm will increase its output. But this is clearly a contradiction because the merging firms will also increase their output if total production z , were reduced, see equation (3.7). All firms, non-merging and merging cannot increase their output if total output decrease. This gives that a merger will increase z , the total number of EVs sold by the industry. We have already seen that increased industry output z , causes the non-merging firms to reduce their output. Thus it must be the case that the merging firms produce more as a result of the merger.

For the merging firms there are two effects that go in the opposite direction: 1. They produce more due to a bigger network size. 2. They produce less due to increased industry output. Clearly, the former effect is dominating for the merging firms all together. But for an individual merging firm, there could exist

cases where the merger reduces the individual output, while increase it for another. This would be in a case of asymmetry. Thus, one cannot say that an increased level of compatibility will increase output for all merging firms, but the merging firms will jointly sell more EVs. With $A - z \geq 0$ we have the following proposition:

Proposition 4. *A higher degree of compatibility will always increase the industry-wide number of EVs.*

Now Proposition 3 and 4 states that a higher degree of compatibility leads to more EVs. Proposition 3 states, in particular, that full compatibility will lead to the highest number of EVs. This is due to the fact that consumers care about their charging opportunities. A bigger charging network is assumed to have more charging stations, which the consumers benefit from. Thus, the biggest network possible, represented by full compatibility, results in the highest number of consumers choosing an EV in favor of a gasoline- or diesel car. But this is not what we observe in the charging market, where Tesla has made their charging stations incompatible with all other EV brands. And it may very well be that other EV brands follow in the footsteps of Tesla. In the following chapter I will address this by comparing the private and social incentives for achieving compatibility.

CHAPTER 4

The Private- and Social Incentives for Compatibility

To be able to compare the private and social incentives for charging compatibility, the private and social benefits have to be defined. In equation (3.1) we derived that firm i 's equilibrium output level equals the price it receives for an EV in equilibrium, namely p_i . As noted above, this gives that firm i 's gross profits in equilibrium equals $\pi_i = p_i(x_i^*)x_i^* = (x_i^*)^2$. It is only given by the individual production level. The more EVs they sell, the higher profits they get. Remember that the marginal cost is assumed to be zero, hence any positive price will give them positive profits. Aggregate profits of the whole industry is denoted as: $\pi \equiv \pi_1 + \pi_2 + \dots + \pi_n$.

As explained in Chapter 2, the expected consumer surplus for a single consumer is given by (2.1):

$$r + v(y_i^e) - p_i$$

Inserting for the equilibrium price: $p_i = A + v(y_i^e) - z$, from equation (2.4) yields:

$$r + v(y_i^e) - A - v(y_i^e) + z$$

$$r + z - A$$

Which gives the consumer surplus as function of the total number of EVs: z . From this we can derive the sum of expected consumer surplus of all consumers. Only those consumers with non-negative surplus enter the EV market:

$$r + z - A > 0$$

$$r > A - z$$

Using the fact that r is uniformly distributed between minus infinity and A , the consumers with r between $(A - z)$ and A enter the market. Integrating over all consumers who enter the market gives the sum of expected consumer surplus of all consumers. β represents the r which we are integrating with respect to:

$$\begin{aligned}
S(z) &= \int_{A-z}^A (\beta + z - A) d\beta \\
&= \left[\frac{1}{2}\beta^2 + z\beta - A\beta \right]_{A-z}^A \\
&= \left(\frac{1}{2}A^2 + zA - A^2 \right) - \left(\frac{1}{2}(A-z)^2 + z(A-z) - A(A-z) \right) \\
&= zA - \frac{1}{2}A^2 - \left(\frac{1}{2}(A^2 - 2zA + z^2) + zA - z^2 - A^2 + zA \right) \\
&= zA - \frac{1}{2}A^2 - \frac{1}{2}A^2 + zA - \frac{1}{2}z^2 - zA + z^2 + A^2 - zA \\
&= z^2/2
\end{aligned} \tag{4.1}$$

In any fulfilled expectations equilibrium, expected- and actual consumer surplus will be equal because the expectations are fulfilled. Hence the expected consumer surplus given in (4.1), can be used when discussing actual consumer surplus. We see that the consumer surplus only depend upon the total number of EVs: z . This follow from two effects: 1. The more supply of EVs, the lower is the equilibrium price, which increase each consumer's surplus. 2. Lower equilibrium price will in addition make more consumers enter the EV market because the marginal consumer is pushed to the left in the uniform distribution. In other words, more consumers will chose an EV in favor of gasoline- or diesel car.

Following Katz and Shapiro (1985), I will use the sum of producer- and consumer surplus as the social welfare measure. However I will add an environmental cost representing the emission costs of gasoline- and diesel cars. In this model, all consumers M are assumed to buy a car, either an electric or a gasoline- or diesel car. All the consumers who end up buying a gasoline- or diesel car: $(M - z)$, will emit greenhouse gases and harm the environment. The environmental cost is

assumed to enter linearly in the welfare measure: $\gamma(M - z)$, where γ represents the environmental cost of a gasoline- or diesel car in terms of how much it emits. One more EV will increase z by one, and decrease the environmental cost by γ .

The total environmental cost from gasoline- and diesel cars is denoted: $\Gamma = \gamma(M - z)$, which gives that in any fulfilled expectations Cournot equilibrium, welfare gross of the fixed cost of compatibility is given by:

$$W(x_1, \dots, x_n) = \pi(x_1, \dots, x_n) + S(x_1 + \dots + x_n) - \Gamma = \sum_{i=1}^n x_i^2 + z^2/2 - \gamma(M - z) \quad (4.2)$$

When analyzing the incentives for achieving compatibility, the change in the different profits and surpluses will be compared to the fixed costs of achieving compatibility F_i . In particular, a firm's change in profit is denoted as: $\Delta\pi_i = \pi_i^C - \pi_i^I$, and the change in the industry's joint profits as: $\Delta\pi = \sum_{i=1}^n \Delta\pi_i$. The change in the social welfare measure is given by: $\Delta W = W^C - W^I$, the change in consumer surplus by: $\Delta S = S^C - S^I$, and the change in environmental cost by: $\Delta\Gamma = \Gamma^C - \Gamma^I$, which gives that the change in welfare can be denoted: $\Delta W = \Delta\pi + \Delta S + \Delta\Gamma$. The society will have an incentive to achieve compatibility if the change in social welfare exceeds the compatibility costs. While the private manufacturers will have an incentive if the change in joint profits exceeds the joint costs of compatibility. An individual manufacturer will have an incentive if the change in profits exceeds the compatibility costs: $\Delta\pi_i > F_i$.

When discussing how compatibility may be achieved between electric vehicles and charging systems, the two main concepts are: the joint adoption of a product standard or the construction of an adapter. In the former, a given set of EV manufacturers or the industry as a whole act together to make their EVs and different charging systems compatible. While in the latter, an EV manufacturer can in principle act on its own to make its EVs compatible with the charging system of others.

There might exist cases where firms will disagree on the desirability of making their charging systems compatible. As stated above, a coalition of merging firms

will always produce more, but this is not necessarily the case for each individual firm in the coalition. A good example of this is shown in the Extension in Chapter 5, where I analyze an asymmetric case. In short, the idea is that if a large- and a small firm is to form a coalition, the large firm might lose more than it gains. This is because the small firm increase its production so much, that it drives down the price of the large firm. In other words, a firm may lose profits on a move to increased compatibility. But since the number of EVs sold by the merging firms increase, the coalition in total increase their profits from merging. If the increase in profits are higher than then cost of achieving compatibility, the private incentives should in principle be high enough. But unless negotiation is possible, the profit-losing firm will never agree to make its charging system compatible. Negotiation could for example be side payments from the profit gaining firm to the profit losing one.

4.1. If Side Payments are Feasible

If side payments among all firms are feasible, a set of compensations could be constructed such that all firms earn greater individual profit if compatibility raises joint profits. Basically, what is often referred to as Coasian bargaining in economics: If social welfare is increased at the expense of decreased welfare for some, everyone could be made better of with proper compensations. In this case: If a move to increased compatibility would raise joint profits, a set of side payments could be made such that everyone is equally well- or better off.

We know that both the private profit and consumer surplus will increase, and that the environmental costs will decrease, if the number of EVs goes up. Proposition 3 states that the number of EVs under complete compatibility is always greater than under less than complete compatibility. In other words, a move to complete compatibility would increase social welfare. Whether the move will be made depends upon the size of the fixed cost of achieving compatibility.

Proposition 5. *When the costs of compatibility are fixed, any move to full compatibility which increase industry profits, is socially beneficial.*

Proposition 5 states that if the EV industry finds the move to complete compatibility profitable, then the same yields for the society as a whole. However, it is possible to find cases where the society benefit from a move to complete compatibility, while the private sector does not. Remember that both consumer surplus and joint profits are increased, and that environmental costs are reduced from a move to full compatibility. Hence the increase in social welfare is always greater than the increase in joint private profits: $\Delta W > \Delta\pi$. Now if the industry-wide costs of achieving compatibility F are higher than the change in private profits, but lower than the increase in social welfare: $\Delta\pi < F < \Delta W$, the private incentives are inadequate. The EV manufacturers will fail to agree upon complete compatibility even though it is socially desirable. This is due to the fact that the firms cannot appropriate all the benefits of compatibility.

Proposition 6. *Even when side payments among all EV manufacturers are feasible, the manufacturers may fail to achieve full compatibility in cases where full compatibility is socially optimal.*

4.2. The Adoption of an Industry Standard

One of the ways of achieving compatibility is through the joint adoption of an industry standard. In reality this would be to develop a charging technology which is compatible with all the EV brands that participate in making the standard. An industry standard do not need to be adopted by the entire industry, it could just be a subgroup of all the firms. The EV manufacturers must jointly decide to make their charging systems compatible. Any firm can veto the move to compatibility. Therefore, if no side payments are feasible, the standard will be made if and only if all firms joining the standard benefit from its creation. When the costs of making and adopting the standard is F_i , the adoption will occur if and only if $\Delta\pi_i > F_i$ for all adopters of the standard.

If side payments are feasible among the manufacturers adopting the standard, a sufficient condition for achieving compatibility is that the joint profits of the manufacturers achieving compatibility rise. Formally, if k firms are to make a standard and side payments are feasible, a sufficient condition is that their joint profits increase more than their incurred costs:

$$\sum_{i=1}^k \Delta\pi_i > \sum_{i=1}^k F_i$$

In this case, the firms that lose profit from adopting the standard, can be properly compensated by the firms that earn greater profits from it. While if side payments are not feasible, all firms k have to benefit from the standard if it is to be created:

$$\Delta\pi_i > F_i \text{ for } i = 1, 2, \dots, k.$$

It is clear that it is easier to achieve compatibility if side payments are feasible. Instead of all firms preferring the standard, it is enough that firms in aggregate do.

Proposition 7. *The private rule for making a standard is more stringent when side payments are infeasible than when they are feasible. The number of situations where the EV manufacturers fail to adopt a socially beneficial standard is therefore greater.*

However, keep in mind that the side payments are assumed to be associated with no transaction costs.

4.3. The Construction of an Adapter

In the adapter case, a manufacturer can act unilaterally to make its EV compatible with the charging system of another network. However, firms may have incentives to block the creation of an adapter because it might decrease their profits. We can think of it as side payments made to block any attempt of making an adapter, for example through legal channels.

If such side payments are not feasible, an adapter will be constructed as long as at least one manufacturer benefits on the move to compatibility. It is fair to assume that the manufacturer making the adapter is the only one to bear the compatibility cost. Thus, firm i 's private incentive to construct an adapter is: $\Delta\pi_i > F_i$, while the social incentive depends upon: $\Delta\pi_i + \sum_{j \neq i} \Delta\pi_j + \Delta S + \Delta\Gamma - F_i$. The change in the other firms profits, the consumer surplus and the environmental cost: $\sum_{j \neq i} \Delta\pi_j + \Delta S + \Delta\Gamma$, may in general be either positive or negative. This implies that the private incentives may either be too low or too high from a social welfare point of view.

We can think of a case with two firms, where the firm making the adapter, firm 2, is smaller than its competitor. By making the adapter they increase their charging network, and more consumers will buy their EV. This will lead to a higher supply of EVs, and firm 1 will lose market shares, and their profit will drop $\Delta\pi_1 < 0$. If this effect dominates, in the sense that the profit decrease of firm 1 is bigger than profit increase of firm 2, the incentives for achieving compatibility might be socially excessive. Firm 2's incentives for making the adapter might be higher than the society's incentives, and in particular they might reduce social welfare if exploited. That is, if the cost of achieving compatibility is higher than the increase in social welfare, but lower than the profit increase of firm 2: $\Delta W < F_2 < \Delta\pi_2$, the construction of the adapter may reduce social welfare.

Proposition 8. *Suppose there are only two EV manufacturers, which are associated to incompatible charging networks. A manufacturer with a market share below 50 percent may have excessive incentives to make an adapter, from a social welfare point of view.*

So far we have established that compatibility leads to more EVs. In the symmetric case, it specifically leads to more output and profit for all manufacturers. Whether they would agree to compatibility, is assumed to depend upon the fixed cost of making a standard or an adapter. In particular if the increase in profits is

higher than the costs, compatibility would be the optimal solution. Furthermore we introduced the concept of side payments, which makes more situations with compatibility beneficial for the manufactures.

However, looking outside the model, there are reasons for not becoming compatible other than high costs of making a standard. As briefly discussed, the firms might disagree on the desirability of becoming compatible. This argument is based on the idea that the market structure can be asymmetric. A large manufacturer might not want to share its corresponding large charging network with a small manufacturer. In the following chapter I will conjecture that the future market shares will not be symmetric since some firms have gotten a head start. Specifically, this has led to cost differences among the firms.

CHAPTER 5

Extension - Asymmetric Case

In this extension I will make some adjustments to the assumptions of the model in order to solve for asymmetric equilibriums.

Following Katz and Shapiro I have made the assumption that the network value function is concave. In particular, I have adopted that $v(y)$ is twice continuously differentiable with $v' > 0$, $v'' < 0$, $v(0) = 0$, and $\lim v'(y) = 0$ as $y \rightarrow \infty$. In order to obtain an explicit solution I will ease this assumption by letting the network value function be linear. Formally, I will assume that it takes the following form: $v(y) = \alpha y$, where α is a constant between 0 and 1. This gives that one more member of the charging network, increase the consumers willingness to pay with α . In the original case, this effect was decreasing at the margin, but now an additional consumer will always have the same effect. However, in the narrow interval of y we are looking at, a linear function is a good approximation of the concave network value function $v(y)$.

As before, the demand function of the consumers is given by:

$$p_i = A + v(y_i^e) - \sum_{i=1}^n x_i,$$

inserting for the new value function: $v(y) = \alpha y$, yields:

$$p_i = A + \alpha y_i^e - \sum_{i=1}^n x_i \tag{5.1}$$

Further I will restrict the industry to only consist of two manufacturers: $n = 2$, denoted 1 and 2. Originally, the marginal costs of production c , was assumed to be equal for all manufacturers, and in particular equal to the normalized unit cost of gasoline- and diesel cars, which was set to zero. This was based on the fact that the

cost differences of today are mainly due to economics of scale, and will even out as the production of EVs increase in scale. However, the different manufacturers are on different stages when it comes to upgrading their productivity. As mentioned in the Introduction, Mercedes just released their plans for making a new production line only for EVs, called EQ.¹ Tesla on the other hand opened their Gigafactory for mass production of EVs in July this year, two years after they started the building process.²

Thus, the different EV manufacturers are likely to utilize advantage of scale at different points in time. Accordingly I will ease the assumption that the different manufacturers face the same marginal costs. In particular I will assume that manufacturer 1 is more cost efficient: $c_1 < c_2$. It is natural to think of Tesla as the cost efficient manufacturer in this case.

The model is still in form of a Cournot game where the firms choose their quantity simultaneously. But now the firms' maximization problems will differ due to different marginal costs. Each firm maximize its profits given the quantity chosen by the other firm, and given the consumers expectations regarding network sizes:

$$\max_{x_i} \pi_i = (p_i - c_i)x_i$$

inserting for the equilibrium price gives:

$$\max_{x_i} \pi_i = (A + \alpha y_i^e - \sum_{i=1}^n x_i - c_i)x_i$$

The maximization problem has the following first order condition:

$$(A + \alpha y_i^e - \sum_{i=1}^n x_i - c_i) + x_i(-1) = 0,$$

¹First paragraph, Section 1.1.1 The Current Market.

²https://en.wikipedia.org/wiki/Gigafactory_1

which gives that the equilibrium sales levels (x_1^*, x_2^*) must satisfy:

$$x_i^* = A + \alpha y_i^e - \sum_{j=1}^n x_j^* - c_i \text{ for } i = 1, 2. \quad (5.2)$$

In the following I will solve for the unique equilibrium output and -price, and compute each firm's derived profits. First under complete incompatibility, then under complete compatibility. Then, I will compare the two profits, and see if there exist situations where the cost efficient manufacturer might prefer to have an incompatible charging system, like for example Tesla have today. If so, will side payments make compatibility more feasible. And more interestingly, what happens to social welfare in either case.

5.1. Complete Incompatibility

Complete incompatibility is the case where each firm's sales makes up their network size: $y_i = x_i$. Inserting this into equation (5.2) we can solve for the explicit equilibrium output level for each firm:

$$x_1 = \frac{1}{2 - \alpha}(A - x_2 - c_1) \quad (5.3)$$

$$x_2 = \frac{1}{2 - \alpha}(A - x_1 - c_2) \quad (5.4)$$

Solving equation (5.3) and (5.4) simultaneously for x_1 and x_2 gives the unique Cournot equilibrium in the case of complete incompatibility:

$$x_1^I = \frac{1}{3 - 4\alpha + \alpha^2}(A(1 - \alpha) - (2 - \alpha)c_1 + c_2) \quad (5.5)$$

$$x_2^I = \frac{1}{3 - 4\alpha + \alpha^2}(A(1 - \alpha) - (2 - \alpha)c_2 + c_1) \quad (5.6)$$

With $a \in (0, 1)$, both equation (5.5) and (5.6) are clearly defined, where x_1^I and x_2^I denotes the equilibrium output level in the case of complete incompatibility. Not surprisingly, what makes them differ is the different marginal costs. We see that whoever is the most cost efficient will produce the most: $c_1 < c_2$ gives $x_1^I > x_2^I$.

Inserting the equilibrium quantities back into the expression for the equilibrium price gives the price each manufacturer receives in equilibrium:

$$p_1^I = \frac{1}{\alpha^2 - 4\alpha + 3} (A(1 - \alpha) + c_1 + c_2 - (3 - \alpha)\alpha c_1)$$

$$p_2^I = \frac{1}{\alpha^2 - 4\alpha + 3} (A(1 - \alpha) + c_1 + c_2 - (3 - \alpha)\alpha c_2)$$

The more cost efficient receives a higher price in equilibrium. In ordinary Cournot competition, where the network effect is absent, the two firms receive the same price in equilibrium. With different marginal costs however, they will produce different quantities. But the cost efficient firm will not be able to charge a higher price like we see here. This is because the goods are perfect substitutes without the network effects.

With expressions for both the equilibrium quantity and the -price, we can derive the equilibrium profits:

$$\pi_1^I = \left(\frac{A(1 - \alpha) - (2 - \alpha)c_1 + c_2}{\alpha^2 - 4\alpha + 3} \right)^2$$

$$\pi_2^I = \left(\frac{A(1 - \alpha) - (2 - \alpha)c_2 + c_1}{\alpha^2 - 4\alpha + 3} \right)^2$$

Which fits well with the observations done so far, namely that the most cost efficient firm will produce the most, and receive the highest price, and thus obtain the highest profit in equilibrium: $c_1 < c_2$ gives $\pi_1^I > \pi_2^I$. In fact, as in the general model, the profits are equal to the square of the equilibrium output: $\pi_i^I = (x_i^I)^2$, for $i = 1, 2$.

5.2. Complete Compatibility

In the case of complete compatibility each firm will have an associated network equal to $y_1 = y_2 = x_1 + x_2$. Again, inserting this into equation (5.2) we can solve

for the explicit output levels:

$$x_1 = \frac{1}{2-\alpha}(A - (1-\alpha)x_2 - c_1) \quad (5.7)$$

$$x_2 = \frac{1}{2-\alpha}(A - (1-\alpha)x_1 - c_2) \quad (5.8)$$

Solving equation (5.7) and (5.8) simultaneously for x_1 and x_2 gives the unique Cournot equilibrium in the case of complete compatibility:

$$x_1^C = \frac{1}{3-2\alpha}(A - (2-\alpha)c_1 + (1-\alpha)c_2) \quad (5.9)$$

$$x_2^C = \frac{1}{3-2\alpha}(A - (2-\alpha)c_2 + (1-\alpha)c_1) \quad (5.10)$$

With $\alpha \in (0, 1)$, the equilibrium outputs x_1^C and x_2^C are clearly defined, where superscript "C" denotes: compatibility. Also in the case of complete compatibility the most cost efficient will produce the most: $c_1 < c_2$ gives $x_1^C > x_2^C$. Inserting the equilibrium outputs in the price function gives the equilibrium prices:

$$p_1^C = \frac{1}{3-2\alpha}(A + (1-\alpha)(c_1 + c_2))$$

$$p_2^C = \frac{1}{3-2\alpha}(A + (1-\alpha)(c_1 + c_2))$$

Which are equal to each other, because each firm is associated to the same network. Inserting back back into the expression for the profit for the equilibrium output and -price gives the equilibrium profits:

$$\pi_1^C = \left(\frac{A - (2-\alpha)c_1 + (1-\alpha)c_2}{3-2\alpha} \right)^2$$

$$\pi_2^C = \left(\frac{A - (2-\alpha)c_2 + (1-\alpha)c_1}{3-2\alpha} \right)^2$$

Since the two firms face the same price, and the most cost efficient produce the most, it will also earn the greatest profit: $c_1 < c_2$ gives $\pi_1^C > \pi_2^C$. We can see that the profits is given by the squared level of output: $\pi_i^C = (x_i^C)^2$, for $i = 1, 2$.

5.3. Incentives for Incompatibility?

In the equilibrium characterized by a symmetric oligopoly in Section 3.2.1, all the firms will benefit from a move to full compatibility because everyone will experience increased output and profit. But with asymmetry, this is not necessarily the case. If the two manufacturers become compatible, they will both increase their associated network. Since manufacturer 2 produce less in the case of incompatibility, it will experience a larger increase in network size. Accordingly manufacturer 2 will increase its production more than manufacturer 1. However, increased industry output has a negative effect on both manufacturers output levels as it drives down the price. Hence, there might exist situations where the cost efficient manufacturer will lose on a move to compatibility. This all depends on the size of the network effect, given by the parameter: α .

For manufacturer 1 to have an incentive for remaining incompatible, it must earn greater profits by doing so. As a tie-breaking rule, manufacturer 1 is assumed to stay incompatible if indifferent between becoming compatible or not. I will thus solve $\pi_1^I = \pi_1^C$, for α :

$$\left(\frac{A(1-\alpha) - (2-\alpha)c_1 + c_2}{\alpha^2 - 4\alpha + 3} \right)^2 = \left(\frac{A - (2-\alpha)c_1 + (1-\alpha)c_2}{3 - 2\alpha} \right)^2 \quad (5.11)$$

If equation (5.11) has a reasonable solution for α , there will exist situations where the cost efficient manufacturer would prefer to stay incompatible. Restricting c_1 to be less than c_2 , gives that equation (5.11) has three solutions for α . The first one is the trivial one with $\alpha = 0$. With α equal to zero there is no network effect, and the choice of compatibility becomes irrelevant for both the consumers and manufacturers. The two other solutions are characterized by:

$$\alpha = \frac{1}{c_1 - c_2} \left(\frac{1}{2}A + 2c_1 - \frac{5}{2}c_2 - \frac{1}{2}\sqrt{(A - c_2)(A + 4c_1 - 5c_2)} \right) \quad (5.12)$$

$$\alpha = \frac{1}{c_1 - c_2} \left(\frac{1}{2}A + 2c_1 - \frac{5}{2}c_2 + \frac{1}{2}\sqrt{(A - c_2)(A + 4c_1 - 5c_2)} \right) \quad (5.13)$$

In order to see if either of them could fit the parameter restriction of $\alpha \in (0, 1)$, I will perform a numerical analysis.

5.4. Numerical Analysis

So far we have assumed that the marginal cost of an EV is equal to that of a gasoline- or diesel car. This was backed up by the fact that the cost difference of today are mainly caused by economics of scale, and as we are considering the period 2020-2030 they were assumed to even out before 2020. In this numerical analysis however, we step away from this assumption and instead assume that the cost differences of today will be maintained.

Since the marginal cost of a gasoline- and diesel car is normalized to zero, the marginal cost of an EV is the additional cost over the unit cost of a gasoline- or diesel car. Thus, when measuring the additional cost we compare the price level of an EV and a gasoline- or diesel car before taxes. As representative EVs I will use: Tesla Model 3 and Opel Ampera-e. Sales have not officially started in Norway, but they are said to have the start price of 35 000 dollars (280 000 NOK) and 37 500 dollars (300 000) respectively.³ These prices are not subjected to taxes, hence I can compare them to the average price of similar gasoline- and diesel cars before taxes. In the analysis of social costs of EVs newly made by the Norwegian Environment Agency, they use that the average price of a big gasoline- or diesel car is 215 000 NOK before taxes (Norwegian Environment Agency, 2016). Using this as a reference gives the following marginal cost levels: $c_1 = 280 - 215 = 65$, $c_2 = 300 - 215 = 85$.

The parameter left to set is A , which denotes the consumer with the highest willingness to pay for an EV regardless of the associated charging network. It is reasonable to think that there exist some electric vehicle enthusiasts, which have high willingness to pay irrespective of the charging system. The EVs can after all be charged at home, and benefit from free parking and free use of bus lanes,

³<https://www.tesla.com/model3>, <http://www.tu.no/artikler/denne-slar-tesla-model-3-pa-rekkevidde/351453>

as explained in the Introduction. In addition, both Model 3 and the Ampera-e have higher performance than an ordinary gasoline- or diesel vehicle, including for example powerful acceleration. As a benchmark case I will set it to be 100 000 NOK above the marginal cost of the most expensive EV: $A = 185$.

Inserting all the fixed parameter values into equation (5.12) and (5.13) gives: $\alpha = 0.62$ and $\alpha = -1.62$, respectively. Hence, there exist a reasonable value for α , namely $\alpha = 0.62$. For any α higher than 0.62, the efficient manufacturer would earn greater profits from having its own incompatible charging system. While for any α below 0.62, the manufacturer would have higher profits with compatibility.

5.4.1. Simulations of individual equilibrium output, -price and -profit

Figure 5.1 shows the number of EVs, prices and profits for different levels of α . Remember, α gives how much the consumers benefit from the EV brand's associated charging network. Along the x-axis in all the four diagrams are the values for α . As the costs are measured in thousands of dollars, so are the prices. Remember that the price- and cost of a gasoline- and diesel car is normalized to zero, hence the price level here denotes how much more the consumers are willing to pay for an EV compared to a gasoline- and diesel car. The quantity- and profit levels are correspondingly denoted in thousands of EVs and thousands of dollars respectively.

From Figure 5.1a we can see that manufacturer 1 would produce slightly more in the case of compatibility (C) than in the case of incompatibility (I), for $\alpha < 0.62$. This is because the positive effect of increased network size exceeds the negative effect of increased industry output. For $\alpha > 0.62$ the situation is reversed, and manufacturer 1 will always produce more in the case of incompatibility. Manufacturer 2 on the other hand will always make more EVs if the brands are compatible. In fact, manufacturer 2 will be driven out of business for sufficiently high values of α , in the case of incompatibility. This is because manufacturer 1 increase industry output to the extent that it drives manufacturer 2's price down to its marginal

cost. Since manufacturer 2 is not able to produce positive output for $\alpha = 0.8$, it does not make sense to look at these simulations for $\alpha > 0.8$, because the choice of compatibility becomes irrelevant if manufacturer 1 has monopoly power. Hence, in this benchmark case, the parameter value of α is restricted to $\alpha \in (0, 0.8)$.

But even though the cost efficient manufacturer could produce more with incompatibility, the industry as whole will always produce more with full compatibility. This is clear from Figure 5.1b. The line indicating industry output with compatibility always lies above the corresponding line with incompatibility.

Figure 5-1a: Individual number of EVs.

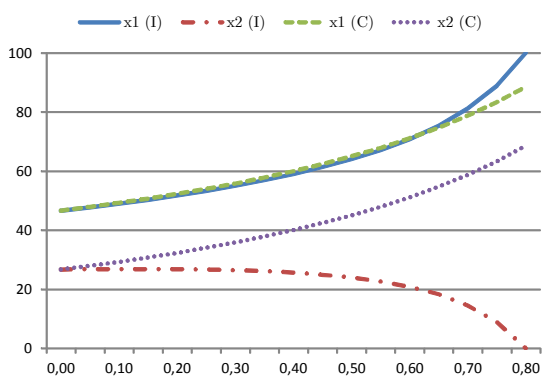


Figure 5-1b: Total number of EVs.

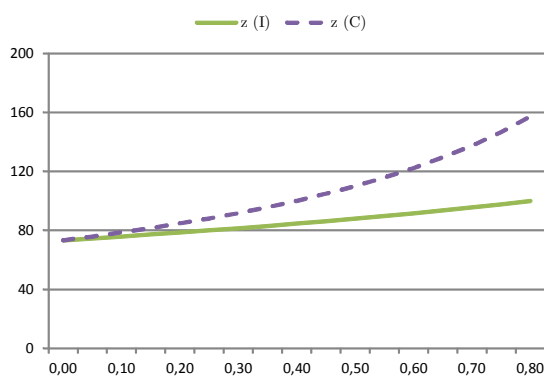


Figure 5-1c: Prices.

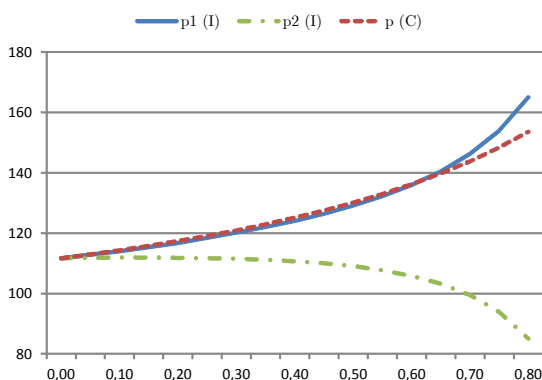


Figure 5-1d: Individual profit.

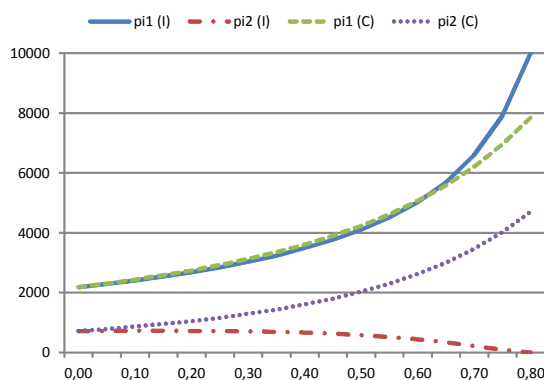


Figure 5.1. Simulations of equilibrium output, -price and -profit under compatibility and incompatibility, in the benchmark case.

Figure 5.1c shows the equilibrium prices. Just as the difference in the two manufacturers' output levels increase with α , so does the prices. As the production level of manufacturer 2 drops to zero when α approaches 0.8, the price manufacturer 2 receives in equilibrium approaches its marginal cost: $p \rightarrow c_2 = 85$.

When the brands are compatible they receive the same price, which both brands are better off with, up to the critical point of $\alpha = 0,62$. After this point, manufacturer 1 would have received a higher price with an incompatible charging system.

The individual firm's profits follow the same pattern as the equilibrium output and -price. As the cost efficient manufacturer 1 produce more, and receives a higher price in the case of incompatibility with $\alpha > 0.62$, it will also earn greater profits. We see that manufacturer 2 always gains from compatibility as the profit with compatibility always is higher than the profit with incompatibility.

5.4.2. Simulations of social welfare

When analyzing the difference in welfare I will use the same welfare measure as derived above in equation (4.2):

$$W(x_1, x_2) = \pi(x_1, x_2) + S(x_1 + x_2) - \Gamma = (x_1)^2 + (x_2)^2 + z^2/2 - \gamma(M - z)$$

It is given by the industry profits, consumers surplus and environmental costs of gasoline- and diesel cars. The environmental cost is given by the amount of gasoline- and diesel cars times a constant cost, given by the average cost of emissions. As mentioned in the Introduction, a gasoline- or diesel car has an average lifetime of 19 years.⁴ According to Statistics Norway, Norwegian car owners drive on average 12 000 km a year.⁵ This gives that a gasoline- or diesel car drives on average 228 000 km. How much it will emit depends upon the specific car and driving patterns. The Institute of Transport Economics use in one of their reports that a gasoline- or diesel car on average emit 106 grams of CO_2 per kilometer

⁴Fourth paragraph, Section 1.1. The EV- and Charging Market.

⁵<https://www.ssb.no/k/reg/>

(Figenbaum and Kolbenstvedt, 2013). I will adopt this number, which gives that a gasoline- or diesel car emits approximately 24 tons of CO_2 on average.

When determining how much all these emissions cost I will use IPCC's estimated carbon price for 2030, which is set to approximately 100 dollars per ton of CO_2 (IPCC, 2014). All together this gives that a gasoline- or diesel car on average will cost the environment approximately 20 000 NOK. Hence, I will set the constant environmental cost equal to $\gamma = 20$.

In order to derive the total environmental cost, the total number of consumers M , needs to be set. The objective with the environmental cost is to show that the choice of compatibility not only leads to different profits and consumer surpluses, but also to different cost for the society through more emissions. Since compatibility leads to the highest number of EVs in total, specifically $z^C = 157$, with $\alpha = 0, 8$, I will normalize M to 157. In this way, it will be easy to identify the environmental costs both in case of incompatibility and with different levels of the network effect α .

The simulations of how industry profits, consumer surplus, environmental costs and welfare varies with α are shown in Figure 5.2. Both industry profits and consumer surplus will be higher in the case of complete compatibility as seen from Figure 5.2a and 5.2b. Which is not surprising, because both industry profits and consumer surplus is determined by total output, which always is greater with compatibility. And since compatibility always leads to more EVs, there is less gasoline- and diesel cars on the roads. This gives that the environmental cost will be lower, see Figure 5.2c.

Since the industry profits and consumer surplus is always higher, and environmental cost always lower, the social welfare will always be greater with compatibility.

Figure 5-2a: Industry profits.

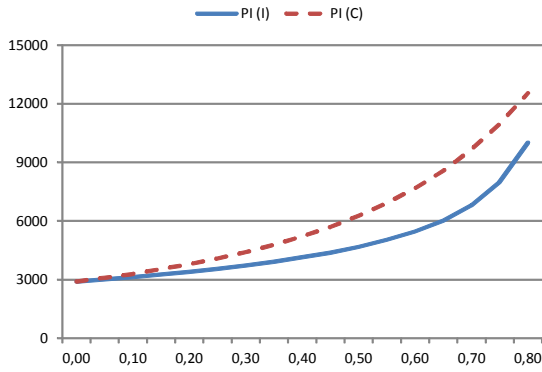


Figure 5-2b: Consumer surplus.

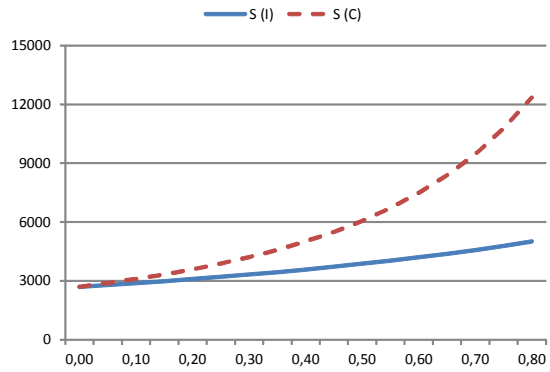


Figure 5-2c: Environmental cost.

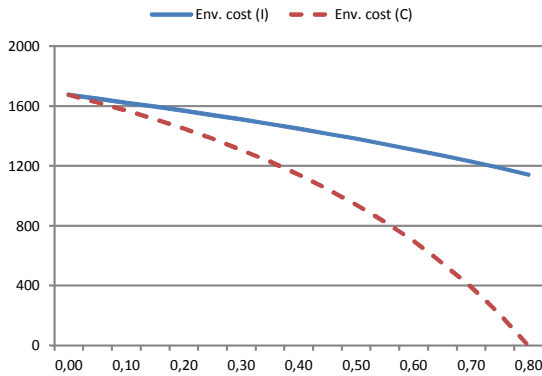


Figure 5-2d: Social welfare.

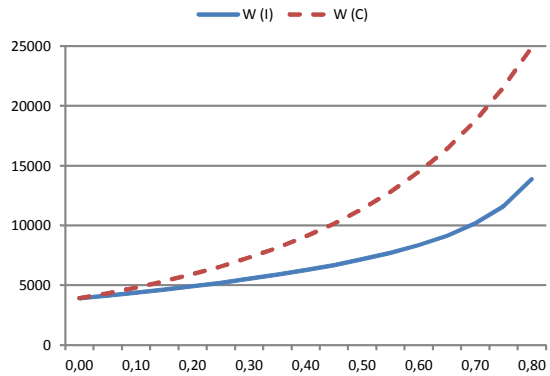


Figure 5.2. Simulations of industry profits, consumer surplus, environmental costs and social welfare under compatibility and incompatibility, in the benchmark case.

5.4.3. Private and Social Incentives for Compatibility with Asymmetry?

Going back to the discussion in Chapter 4, about the discrepancy between private and social incentives for achieving compatibility, we had that in the symmetric case, all firms would benefit on a move to compatibility. Whether they will make the transition, comes down to the cost of compatibility F_i .

In this constructed example with two EV manufacturers however, we have just seen that there might exist situations where the private disagree on the desirability of achieving compatibility, even with $F = 0$. In particular situations where the cost efficient manufacturer does not benefit from making its charging system compatible. For sufficiently high values of α , the efficient manufacturer would be

better off having an incompatible charging system. The inefficient manufacturer on the other hand will always favor compatibility.

When the brands disagree on becoming compatible, side payments could make more situations with compatibility profitable for both. If such situations are to exist, the industry profits with compatibility would have to exceed the private profits of the efficient producer. From Figure 5.2a we see that this will always be the case, as the industry profits under compatibility exceeds the industry profits under incompatibility for all values of α . Thus, when side payments are feasible, all situations would make compatibility achievable, not only those with $\alpha < 0$, 62.

The fact that industry profits would have been greater with compatibility in those situations where the efficient manufacturer prefers incompatibility, means that the social welfare also would have been greater. In fact, the social welfare would have been even higher with compatibility, because the consumer surplus is always higher, and the environmental cost always lower, with compatibility. Thus, there might exist situations where the cost efficient producer favors incompatibility, while the industry and the society as a whole will always be better off with compatibility.

CHAPTER 6

Discussion and Conclusion

In this thesis I have presented a model to analyze the relationship between the choice of compatibility and the diffusion of EVs. The compatibility decision has been treated exogenously, and we have derived the different individual- and industry-wide outputs under both full compatibility and -incompatibility. With fulfilled expectations there exist unique symmetric equilibriums in both extremes.

Furthermore we have analyzed the output effects related to the choice of compatibility. A higher degree of compatibility, here represented with a merger between any two manufacturers, will always increase the industry-wide output of EVs. It follows that the highest degree of compatibility, namely complete compatibility represented with a universal standard, leads to the highest number of EVs. If Norway ends up in a situation with high degree of incompatibility, the transformation of the car fleet will take much longer time. This in turn makes the commitments to the Paris Agreement more difficult to fulfil.

In determining the private- and social incentives for achieving compatibility, the private profits and social welfare were compared to a fixed cost of achieving compatibility. This cost was assumed to represent the coordination cost incurred by manufacturers when developing a standard charging system or an adapter. Followingly we find that if the move to full compatibility is beneficial for the industry, it would be so for the society as well. This is because it leads to more EVs, which is not only beneficial to the society because of increased profits, but also due to increased consumer surplus and lower environmental costs. Thus, there is a discrepancy between social welfare and private profits, which provide the basis for situations where the private industry has insufficient incentives from a social

welfare point of view. The inclusion of side payments improves this to some extent, by making more situations with compatibility beneficial for the manufacturers.

Keep in mind that the discrepancy between private profits and social welfare might be exaggerated since environmental policies are held outside the model. The social welfare measure includes an environmental cost for each gasoline- or diesel car bought at the expense of an EV. This cost is assumed to equal the environmental damage caused by a gasoline- or diesel car's emissions. Thus, by including a Pigou tax on gasoline- and diesel cars, the environmental costs would be corrected for. The welfare measure would then only consist of private profits and consumer surplus. It would still be a discrepancy, but it would be smaller.

We then turned to the possibility of an asymmetric market structure, where we found that even though the society most of the times will benefit from compatibility, this is not necessary the case for the individual brands. As shown in the asymmetric case, a cost efficient brand may very well have strong incentives for staying incompatible, irrespective of the compatibility costs. In this analysis the incentives were based on cost differences. However, we could have made a similar analysis by letting the two brands be associated to charging networks of different quality. Specifically, this could have been done by letting the two brands be associated to different α 's, indicating that one of them has a superior charging network. The brand with the superior network would then most likely have incentives for remaining incompatible for given values of α .

With this in mind, it seems evident that governmental intervention is called for when the market suffer from a high degree of incompatibility. But as the EV manufacturers are big multinational corporations, the government's set of policy instruments is rather limited. In the case of Tesla, the Norwegian government cannot enforce Tesla to open their Superchargers to all electric vehicles. They could however have denied Tesla the permission to build the charging stations in the first place. Whether this would have affected Tesla to rethink their openness

is hard to imagine. A denial would then just seem to punish all Tesla owners, as they are deprived of their opportunity to make use of Superchargers.

Another political measure could be to build-, or fund charging stations open for all EVs, which is exactly what the Norwegian government started with in 2009. As explained in the Introduction,¹ Enova has been the authority responsible for coordinating funds to the building of charging infrastructure. This has led to a steep growth in the number of chargers installed since the beginning of this decade. But a substantial part of the charging stations put up, are ordinary charging stations where it takes several hours to recharge the battery. This is not competitive to the “charging systems” of conventional cars, which are the ones the EVs have to outcompete.

Since more gasoline- and diesel car owners are likely to make the transition to EVs, the faster the charging system becomes, it is essential that the government sponsors the fastest charging technology available. However, as the EV- and charging industry is experiencing rapid technological progress, this could be challenging. Now if the government fails to follow this technological development, they should at least not support charging infrastructure that is not prepared for future charging systems.

The effect which chargers have been able to support has constantly increased. Today, the most commonly used quick charger can charge with an effect of 50 kilowatts. But as Tesla has developed a more powerful charger, it would seem very reactionary to sponsor charging stations that are not ready to be upgraded with more powerful chargers. Tesla’s Supercharger has been around for some years, and the other EV manufacturers cannot be far behind in developing a similar charger. All new charging stations should thus as a minimum be dimensioned to handle the power of a Supercharger.

When it comes to subsidizing charging infrastructure, one could also argue that the government should fund Tesla’s Superchargers under the condition that Tesla

¹Fourth paragraph, Section 1.1.1. The Current Market

opened them for all EVs. Today, Tesla Model S and -X are the only models that can receive power with such great effect. A subsidy to Superchargers would thus seem to only benefit Tesla. But making the Superchargers public might incentivize other EV manufacturers to upgrade their technology. Norway has become a significant EV market, and according to the politicians ambitious targets related to zero-emission vehicles, it will continue to grow. A funding scheme like this is then likely to have an effect on the global EV manufacturers.

As mentioned, the EV- and charging industry has experienced rapid technological progress over the last couple of years. Progress that has led to many innovations when it comes to both battery capacity and charging efficiency, which indisputably has increased social welfare. This is partly due to a high level of competition among the EV manufacturers. Thus, at this point, it is not given that a benevolent social planner would find it optimal to enforce full compatibility. Enforcing full compatibility would here be to restrict the industry to a universal charging technology. This might restrain the manufacturers' incentives for innovation because there would be little or no benefits from developing a new technology. If the quick charging network of today were enforced as a universal standard, the Ultra E project with their "Ultra-Fast-Charging" network had most likely never been started.² In other words, the society can potentially miss out on welfare increasing innovations by restricting the industry to a standard.

In fact, Katz and Shapiro (1986b) discover that firms that are going through an early phase of intense competition, might find it optimal to become compatible to its rivals in order to reduce competition. In other words, if the industry is not restrained by the government, it might find it optimal to "restrain" itself, to avoid competition. Using these results, a social planner might actually find it optimal to encourage competition in a market with technological progress.

These latter arguments related to competition and innovations are highly relevant when discussing optimal policy. It would however require a much richer

²See third paragraph, Section 1.2. Point of Departure.

model, including both dynamics and some sort of R&D decision to incorporate such aspects. But despite the model's limitations, I still think it provide some important insight for policy makers. Namely, how the degree of compatibility can be a key determinant of the total number of EVs, and how the individual manufacturers' incentives for compatibility are formed.

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Appendix. Unique Cournot Equilibrium

In order to derive the unique Cournot equilibrium for three firms, we set $n = 3$ and solve equation (3.1) simultaneously for all three firms:

$$x_1^* = A + v(y_1^e) - (x_1^* + x_2^* + x_3^*)$$

$$x_2^* = A + v(y_2^e) - (x_1^* + x_2^* + x_3^*)$$

$$x_3^* = A + v(y_3^e) - (x_1^* + x_2^* + x_3^*),$$

rearrange to get:

$$x_1^* = \frac{A + v(y_1^e) - (x_2^* + x_3^*)}{2} \tag{6.1}$$

$$x_2^* = \frac{A + v(y_2^e) - (x_1^* + x_3^*)}{2} \tag{6.2}$$

$$x_3^* = \frac{A + v(y_3^e) - (x_1^* + x_2^*)}{2}, \tag{6.3}$$

insert (6.3) in (6.2) and solve for x_2^* :

$$\begin{aligned} x_2^* &= \left\{ A + v(y_2^e) - \left(x_1^* + \frac{A + v(y_3^e) - (x_1^* + x_2^*)}{2} \right) \right\} / 2 \\ x_2^* &= \left\{ \frac{2A + 2v(y_2^e) - 2x_1^* - A - v(y_3^e) + (x_1^* + x_2^*)}{2} \right\} / 2 \\ x_2^* &= \frac{A + 2v(y_2^e) - v(y_3^e) - x_1^* + x_2^*}{4} \\ \frac{3}{4}x_2^* &= \frac{A + 2v(y_2^e) - v(y_3^e) - x_1^*}{4} \\ x_2^* &= \frac{A + 2v(y_2^e) - v(y_3^e) - x_1^*}{3} \end{aligned} \tag{6.4}$$

By inserting (6.2) in (6.3) we can derive the similar solution to x_3^* :

$$x_3^* = \frac{A + 2v(y_3^e) - v(y_2^e) - x_1^*}{3} \quad (6.5)$$

Insert (6.4) and (6.5) in (6.1) and solve for x_1^* :

$$\begin{aligned} x_1^* &= \frac{A + v(y_1^e) - (x_2^* + x_3^*)}{2} \\ x_1^* &= \left\{ A + v(y_1^e) - \left(\frac{A + 2v(y_2^e) - v(y_3^e) - x_1^*}{3} + \frac{A + 2v(y_3^e) - v(y_2^e) - x_1^*}{3} \right) \right\} / 2 \\ x_1^* &= \left\{ \frac{3A + 3v(y_1^e) - A - 2v(y_2^e) + v(y_3^e) + x_1^* - A - 2v(y_3^e) + v(y_2^e) + x_1^*}{3} \right\} / 2 \\ x_1^* &= \frac{A + 3v(y_1^e) - v(y_2^e) - v(y_3^e) + 2x_1^*}{6} \\ \frac{4}{6}x_1^* &= \frac{A + 3v(y_1^e) - v(y_2^e) - v(y_3^e)}{6} \\ x_1^* &= \frac{A + 3v(y_1^e) - v(y_2^e) - v(y_3^e)}{4} \\ x_1^* &= \frac{A + 3v(y_1^e) - \sum_{j \neq 1} v(y_j^e)}{3 + 1} \end{aligned} \quad (6.6)$$

By inserting (6.6) back into (6.4) and (6.5) we can obtain the similar result for x_2^* and x_3^* . We see that (6.6) is identical to the general Cournot equilibrium for any given firm i with n firms:

$$x_i^* = \frac{A + nv(y_i^e) - \sum_{j \neq i} v(y_j^e)}{n + 1}$$